BACKWARD EULER DISCRETIZATION
OF FULLY NONLINEAR PARABOLIC PROBLEMS

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Abstract. This paper is concerned with the time discretization of nonlinear evolution equations. We work in an abstract Banach space setting of analytic semigroups that covers fully nonlinear parabolic initial-boundary value problems with smooth coefficients. We prove convergence of variable stepsize backward Euler discretizations under various smoothness assumptions on the exact solution. We further show that the geometric properties near a hyperbolic equilibrium are well captured by the discretization. A numerical example is given.

1. Introduction

Within the past several years, nonlinear evolution equations of parabolic type have attracted a lot of interest, both in theory and applications. This is due to the fact that such equations are increasingly used for the description of processes involving nonlinear diffusion or heat conduction. As examples we mention reaction-diffusion equations that arise in combustion modeling, the Bellman equations from stochastic control and the nonlinear Cahn-Hilliard equation from pattern formation in phase transitions. Further examples are semilinear problems with moving boundaries, such as the Stefan problem that describes the melting of ice.

The knowledge about stability and convergence for time discretizations of nonlinear parabolic problems has also increased considerably. For Runge-Kutta discretizations of semilinear problems, asymptotically sharp error bounds are given in [9]. Optimal convergence results for quasilinear problems in Hilbert spaces can be found in [10], whereas the papers [5] and [13] deal with stability and convergence of quasilinear problems in Banach spaces. Convergence of linearly implicit Runge-Kutta methods for nonlinear parabolic problems is studied in [11]; corresponding results for multistep discretizations can be found in [1] and [3]. For the fully nonlinear situation, however, not that much is known. A reason for this might be that the analytical frameworks for fully nonlinear equations are often quite involved.

The present paper is based on a new and simple framework, given in [12], that extends ideas from the semilinear case to the fully nonlinear one. This is done as...
follows. Consider a parabolic evolution equation

\[ u' = F(u), \quad t > 0, \quad u(0) \text{ given}, \]

on a Banach space \( X \). The nonlinearity \( F \) is defined on an open subset \( D \) of a second Banach space \( D \subset X \) and takes values in \( X \). By linearizing \( F \) around a state \( u^* \in D \), equation (1.1) takes the form of a semilinear problem

\[ u' = Au + f(u), \quad t > 0, \quad u(0) \in D, \]

where \( A \) is a bounded operator from \( D \) to \( X \). Under the assumption that \( A \) generates an analytic semigroup, we have a (formal) representation of the solution \( u \) by the variation-of-constants formula

\[ u(t) = e^{tA}u(0) + \int_0^t e^{(t-\tau)A}f(u(\tau)) \, d\tau, \quad 0 \leq t \leq T. \]  

Since \( f(u(t)) \) is only defined for \( u(t) \in D \), we have to consider the semiflow in \( D \). But as the analytic semigroup \( e^{tA} : X \to D \) behaves like \( C_1 t^{-1} \), the integral on the right-hand side might not exist in \( D \). Consequently (1.2) cannot be used directly.

This is quite different to the semilinear case where intermediate spaces \( V \) between \( X \) and \( D \) are considered. There, under the assumption that the function \( f \) is locally Lipschitz continuous from \( V \) to \( X \), a unique local solution can be constructed by a fixed-point iteration relying on formula (1.2) (see [7] and [15]).

It turns out that the following slight modification of the variation-of-constants formula

\[ u(t) = e^{tA}u(0) + \int_0^t e^{(t-\tau)A}(f(u(\tau)) - f(u(t))) \, d\tau + \int_0^t e^{tA} \, d\tau f(u(t)) \]  

is the basic tool for the analysis of fully nonlinear equations. Within the space of \( \alpha \)-Hölder continuous functions this relation has a precise meaning and is used to prove existence and uniqueness of a local solution (see [12, Section 8]).

The aim of the present paper is to derive existence and convergence results for time discretizations of (1.1). To keep this exposition in a reasonable length and to avoid technical details, we restrict our attention to the backward Euler method, but we allow variable stepsizes. The extension to strongly \( A(\phi) \)-stable Runge-Kutta methods with constant stepsizes will be given in [17]. To our knowledge, this is the first paper that provides rigorous error bounds for variable stepsize discretizations of nonlinear parabolic problems. The proofs are based on a global representation of the numerical method by means of a discrete variation-of-constants formula similar to (1.3).

In Section 2 we give the precise assumptions on the initial value problem (1.1) and we present two examples of nonlinear parabolic initial-boundary value problems that fit into this analytical framework. Besides, we introduce spaces of \( \alpha \)-Hölder continuous sequences on which our discrete framework is based.

Section 3 deals with the existence and uniqueness of the numerical solution, and with convergence. More precisely, we prove in Theorem 3.3 the expected convergence of order one for constant stepsize discretizations of sufficiently smooth solutions. For variable stepsizes and/or less regular solutions, we show convergence of reduced order.

In Section 4 we study the question whether the dynamics of the analytical problem is well captured by the discretization. As an illustration, we consider exponentially stable equilibria and show that the numerical solution locally exists for
all positive times and decays exponentially towards the equilibrium. A numerical
experiment that is in line with our theoretical result is presented.

The auxiliary results for Sections 3 and 4 are finally given in Section 5.

2. Analytical framework and examples

In this section we give the precise hypotheses for (1.1) and further introduce
some notation that will be used throughout the paper.

We work in the analytical framework given by [12]. Let \((X, \| \cdot \|)\) and \((D, \| \cdot \|_D)\)
be two Banach spaces with \(D\) densely embedded in \(X\), and denote by \(D\) an open
subset of \(D\). We consider the abstract initial value problem

\[
(2.1) \quad u'(t) = F(u(t)), \quad t > 0, \quad u(0) \in D.
\]

Derivatives with respect to the argument of a function are henceforth denoted by
a prime. Our assumptions on the nonlinearity \(F\) are the following.

**Assumption 2.1.** We assume that the function \(F : D \to X\) is Fréchet differentiable and that its derivative \(F' : D \to L(D, X)\) has the following properties.

(i) \(F'\) is locally Lipschitz continuous; i.e., for each \(u^* \in D\) there exist \(R > 0\) and
\(L > 0\) such that

\[
(2.2) \quad \|F'(v) - F'(w)\|_{D \to X} \leq L \|v - w\|_D,
\]

for all \(v, w \in D\) with \(\|v - u^*\|_D \leq R\) and \(\|w - u^*\|_D \leq R\).

(ii) For every \(u^* \in D\) the operator \(F'(u^*)\) is sectorial; i.e., there exist \(\theta \in (0, \pi/2)\),
\(\omega_0 \in \mathbb{R}\) and \(M > 0\) such that if \(z \in \mathbb{C}\) and \(|\arg(z - \omega_0)| \leq \pi - \theta\), then \(z - F'(u^*)\)
has a bounded inverse in \(X\) and

\[
(2.3) \quad \| (z - F'(u^*))^{-1} \|_{X \to X} \leq \frac{M}{|z - \omega_0|}.
\]

(iii) For every \(u^* \in D\) the graph-norm of \(F'(u^*)\) is equivalent to the norm of \(D\).

Under these assumptions, it is known that (2.1) has a locally unique solution
(see [12] Theorem 8.1.1). This solution \(u \in C([0, \delta], D) \cap C^1([0, \delta], X)\) has the
regularity property \(u \in C^\alpha_\delta((0, \delta], D)\) for arbitrary \(0 < \alpha < 1\). For the convenience
of the reader we recall the definition of the space \(C^\alpha_\delta\). For a Banach space \((B, \| \cdot \|_B)\),
\(C^\alpha_\delta((0, \delta], B)\) is the space of all bounded functions \(v : (0, \delta] \to B\) such that \(t \mapsto t^\alpha v(t)\)

![Figure 1. Condition (2.3) holds for all \(z\) outside the shaded cone.](image-url)
is $\alpha$-Hölder continuous in $(0, \delta]$. This space is endowed with the norm
\[
\|v\|_{C^\alpha_0((0,\delta],B)} = \sup_{0 < t \leq \delta} \|v(t)\|_B + \sup_{0 < s < t \leq \delta} \frac{\|v(t) - v(s)\|_B}{(t - s)^\alpha} s^\alpha.
\]

We next give two nonlinear initial-boundary value problems that fit into our framework. More examples can be found in [12].

**Example 2.2** (Combustion of a solid fuel, [3, Section 6.7]). Let $U(t,x)$ denote the temperature of a combustible solid fuel at position $x \in [0,1]$ and time $t \geq 0$. A model for the evolution of $U$ is given by the nonlinear initial-boundary value problem
\[
\partial_t U(t,x) = \partial_x \left( k \partial_x U(t,x) \right) + \varphi(U(t,x)), \quad 0 < x < 1, \quad t > 0,
\]
with homogeneous Neumann boundary conditions $\partial_x U(t,0) = \partial_x U(t,1) = 0$ for all $t > 0$ and initial condition $U(0,x) = U_0(x)$ for $0 < x < 1$. We assume that the diffusion coefficient $k$ is twice differentiable, with bounded second derivative, and that it satisfies the uniform ellipticity condition
\[
k(y) + yk'(y) \geq \kappa > 0 \quad \text{for all } y \in \mathbb{R}.
\]
We further suppose that $\varphi$ has a locally Lipschitz continuous derivative and that the initial value $U_0$ is twice continuously differentiable and satisfies the compatibility conditions $U_0'(0) = U_0'(1) = 0$.

Choosing $X = C([0,1])$ and $D = \{v \in C^2([0,1]) : v'(0) = v'(1) = 0\}$ allows us to write (2.1) in the abstract form (2.1) with $u(t) = U(t,\cdot)$ and
\[
F(v) = (k(v')v')' + \varphi(v).
\]
The smoothness assumptions on $k$ and $\varphi$ immediately imply condition (i) of Assumption 2.1 and the ellipticity condition (2.5) implies (ii) and (iii) there.

Equally, it can be shown that our assumptions are satisfied for the Banach spaces $X = L^2(0,1)$ and $D = \{v \in H^2(0,1) : v'(0) = v'(1) = 0\}$. This follows from the well-known embedding $H^1(0,1) \subset C([0,1])$.

**Example 2.3** (Semilinear problem with moving boundary). We consider the semilinear parabolic problem
\[
\partial_t V(t,y) = \partial_y \left( k \partial_y V(t,y) \right) + \varphi\left(V(t,y), \partial_y V(t,y)\right), \quad 0 < y < b(t), \quad t > 0,
\]
with homogeneous Dirichlet boundary conditions $V(t,0) = V(t,b(t)) = 0$ for $t > 0$ and initial condition $V(0,y) = V_0(y)$ for $0 < y < b(t)$. Here the position of the right boundary $b(t)$ is determined by the ordinary differential equation
\[
\partial_t b(t) = \psi(b(t), V(t,b(t)), \partial_y V(t,b(t))), \quad t > 0, \quad b(0) = 1.
\]
We assume that $\varphi$ and $\psi$ have locally Lipschitz continuous derivatives and that $V_0$ is twice continuously differentiable with $V_0'(0) = V_0'(1) = 0$.

The famous Stefan problem that models the melting of ice is of this form by taking $\varphi = 0$ and $\psi(p,q,r) = -\beta r$ with a positive constant $\beta$ (see [16, Section 15.4]).
Changing the variables $U(t, x) = V(t, b(t)x)$ transforms problem (2.10) to the interval $0 \leq x \leq 1$, and we obtain the nonlinear system
\begin{align}
\partial_t U(t, x) &= \frac{\partial_x U(t, x)}{b(t)^2} + \varphi \left( U(t, x), \frac{\partial_x U(t, x)}{b(t)} \right) + \frac{x \partial_b b(t)}{b(t)} \partial_x U(t, x), \\
\partial_t b(t) &= \psi \left( b(t), U(t, 1), \frac{\partial_x U(t, 1)}{b(t)} \right), \quad 0 < x < 1, \quad t > 0,
\end{align}
(2.7)

with boundary conditions $U(t, 0) = U(t, 1) = 0$ for $t > 0$ and initial conditions $U(0, x) = V_0(x)$ for $0 < x < 1$ and $b(0) = 1$.

We choose $X = C([0, 1]) \times \mathbb{R}$ and $D = \{ v \in C^2([0, 1]) : v(0) = v(1) = 0 \} \times \mathbb{R}$, and since the projection $P : C([0, 1]) \to \mathbb{R} : v \mapsto v(1)$ is continuous, the conditions (i), (ii), and (iii) of Assumption 2.1 are again easily verified.

We finish this section by introducing some notation. The aim of the paper is the analysis of backward Euler discretizations of (2.11) which are given as sequences $u_0, u_1, \ldots, u_N$ in $D$, corresponding to a grid $0 = t_0 < t_1 < \cdots < t_N \leq T$. This motivates the consideration of the following discrete norms and seminorms in $X^N$:
\begin{align}
\mu(v) &= \sup_{1 \leq n \leq N} \| v_n \|, \quad \lambda_\alpha(v) = \sup_{1 \leq k < n \leq N} \frac{\| v_n - v_k \|}{(t_n - t_k)^\alpha} t_k^\alpha, \\
\| v \|_\alpha &= \mu(v) + \lambda_\alpha(v),
\end{align}
(2.8a)

for $v = (v_n)_{n=1}^N \in X^N$ and $0 < \alpha < 1$. Analogously, we denote
\begin{align}
\mu_D(v) &= \sup_{1 \leq n \leq N} \| v_n \|_D, \quad \lambda_{D, \alpha}(v) = \sup_{1 \leq k < n \leq N} \frac{\| v_n - v_k \|_D}{(t_n - t_k)^\alpha} t_k^\alpha, \\
\| v \|_{D, \alpha} &= \mu_D(v) + \lambda_{D, \alpha}(v),
\end{align}
(2.8b)

for $v \in D^N$. Further we define $\mu_\beta$ for $0 \leq \beta \leq 1$ and $v \in X^N_{\beta}$ through
\begin{align}
\mu_\beta(v) &= \sup_{1 \leq n \leq N} \| v_n \|_{\beta}.
\end{align}
(2.9)

Here $(X_\beta, \| \cdot \|_\beta)$ denotes the real interpolation space $(X, D)_{\beta, \infty}$ between $X$ and $D$ (see [12] Section 1.2.1). Note that $\| \cdot \|_\alpha$ and $\| \cdot \|_{D, \alpha}$ are discrete versions of the norms $\| \cdot \|_{C^0_\alpha([0, \delta], X)}$ and $\| \cdot \|_{C^0_\alpha([0, \delta], D)}$, respectively.

3. Convergence analysis of the backward Euler solution

In this section we study the backward Euler method for discretizing (2.11) in time. We show that a unique numerical solution exists for finite times, provided that the maximal stepsize is chosen sufficiently small. We further derive convergence estimates under various smoothness assumptions on the exact solution.

We first consider a local situation for which more precise estimates can be obtained. For this, it is convenient to linearize (2.11) around the initial value $u(0)$. This gives the (formally) semilinear problem
\begin{align}
\dot{u} &= Au + f(u), \quad t > 0, \quad u(0) \in D,
\end{align}
(3.1)

where $A = F'(u(0))$ and $f(u) = F(u) - Au$ for $u \in D$. In view of (2.2), there exist $R > 0$ and $L > 0$ such that
\begin{align}
\| f(v) - f(w) \| \leq L_\varrho \| v - w \|_D,
\end{align}
(3.2)

for all $\| v - u(0) \|_D \leq \varrho \leq R$ and $\| w - u(0) \|_D \leq \varrho \leq R$ (see proof of Lemma 5.2).
Since the backward Euler method is invariant under linearization, the numerical approximation $u_n$ to $u(t_n)$ is given by the recursion
\begin{equation}
\frac{u_n - u_{n-1}}{h_n} = Au_n + f(u_n), \quad 1 \leq n \leq N,
\end{equation}
with $t_n = t_{n-1} + h_n$ for $1 \leq n \leq N$ and $t_0 = 0$. Here $h_n > 0$ denotes the stepsize which is chosen according to accuracy requirements. The starting value $u_0 \in D$ is allowed to be different from $u(0)$.

We remark that, due to (2.3) with $u^* = u(0)$ and (3.2), the nonlinear equation (3.3) has a unique solution $u_n \in D$ for stepsizes $h_n$ satisfying $h_n \omega_0 < 1$, as long as $\|u_{n-1} - u(0)\|_D \leq \varrho$ for a certain $\varrho > 0$. In fact, (3.3) can be solved by standard fixed-point iteration (see Lemma 5.2). Let us point out, however, that already after one single step we can only expect
\[ \|u_1 - u(0)\|_D \leq C \varrho, \]
where $C > 1$. Thus, after a finite number of steps, independently of the stepsizes, the validity of (3.2) is no longer guaranteed. Therefore, this step-by-step approach is not suited to construct the numerical solution on a finite time interval $[0, T]$.

In order to overcome this difficulty, we adopt a global approach relying on the discrete variation-of-constants formula
\begin{equation}
(3.4) \quad u_n = r(t_n, 0)u_0 + \sum_{k=1}^n h_k r(t_n, t_{k-1}) f(u_k),
\end{equation}
where the discrete transition operator $r(t_n, t_k)$ is defined by
\begin{equation}
(3.5) \quad r(t_n, t_k) = (1 - h_n A)^{-1} \cdots (1 - h_{k+1} A)^{-1}, \quad 0 \leq k < n \leq N,
\end{equation}
and $r(t_k, t_k) = 1$. Note that this operator is well defined for
\begin{equation}
(3.6) \quad \max_{1 \leq k \leq N} h_k \leq \overline{h}, \quad \text{if } \overline{h} \omega_0 < 1.
\end{equation}

The numerical solution of (3.1) can be constructed by fixed-point iteration in (3.4). This is based on the fact that the nonlinear operator
\begin{equation}
(3.7a) \quad \Phi : B \subset D^N \rightarrow D^N : v \mapsto \Phi(v) = rv_0 + K(f(v)),
\end{equation}
with $r = (r(t_n, 0))_{n=1}^N$, $f(v) = (f(v_n))_{n=1}^N$ for $v = (v_n)_{n=1}^N \in D^N$, and
\begin{equation}
(3.7b) \quad K(w) = \left( \sum_{k=1}^n h_k r(t_n, t_{k-1}) w_k \right)_{n=1}^N \quad \text{for } w = (w_n)_{n=1}^N \in X^N,
\end{equation}
is a contraction for a suitably chosen subset $B$. Unfortunately, it turns out that the interval of existence is limited by the fact that $\|\Phi(u_0) - u_0\|_{D, \alpha}$ has to be sufficiently small, for $u_0 = (u_0, \ldots, u_0)^N$. Thus, nothing can be said about the size of $t_N$ in this approach. This kind of difficulty also appears when constructing the continuous solution (see [12, Theorem 8.1.1]).

However, the global approach based on the convolution operator in (3.7b) turns out to be useful in order to derive preliminary convergence estimates. Eventually, these estimates can be used to establish the existence of the numerical solution for finite times.

Assume for a moment that the backward Euler approximations $u_0, u_1, \ldots, u_N$ to the solution exist. We set $\overline{u}_n = u(t_n)$ and denote the errors by $e_n = \overline{u}_n - u_n$. 

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Inserting the exact solution into the numerical scheme defines the defects $d_n$ by

$$
\frac{\overline{u}_n - \overline{u}_{n-1}}{h_n} = A\overline{u}_n + f(\overline{u}_n) + d_n, \quad 1 \leq n \leq N.
$$

Subtracting (3.3) from this identity gives the error recursion

$$
e = re_0 + K(f(\overline{u}) - f(u)) + K(d),
$$

where $e = (e_1, e_2, \ldots, e_N)^T \in D^N$, etc.

Let $C_3$ and $R$ be the constants provided by Lemma 5.3 for $u^* = u(0)$. We will show below that after a possible reduction of $T$, we may assume that there exists $0 < \varrho \leq R$ such that

$$
\mu_D(\overline{u} - u(0)) \leq \varrho, \quad \mu_D(u - u(0)) \leq \varrho,
$$

(3.9)

$$
C_3C_5(2\varrho + \lambda_D,\alpha(\overline{u})) \leq \gamma < 1,
$$

where $0 < \alpha < 1$ is chosen and $C_5$ is the constant appearing in Lemma 5.3. Taking norms in (3.8) and using Lemmas 5.3, 5.4 and 5.5 yields

$$
\|e\|_{D,\alpha} \leq \frac{1}{1 - \gamma} \left( C_4\|e_0\|_D + \|K(d)\|_{D,\alpha} \right).
$$

(3.10)

Depending on our requirements on the analytical solution, we obtain different bounds for $\|K(d)\|_{D,\alpha}$ and consequently different error estimates (see Theorems 3.1 and 3.2 below). We finally point out that because of

$$
\|e_n\|_D \leq \|e\|_{D,\alpha}
$$

these theorems also provide error estimates in $D$.

**Theorem 3.1.** Let $u : [0, T] \to D$ be a solution of (2.1) with $u'' \in C_{alpha}^N((0, T], X)$ and assume that

$$
C_3C_5 \left( 2\|u - u(0)\|_{L^\infty([0,T], X)} + \|u\|_{C_{alpha}^N([0,T], D)} \right) < 1,
$$

(3.11)

where $C_3$ and $C_5$ are the constants provided by Lemmas 5.3 and 5.4 for $u^* = u(0)$.

Suppose that either

(a) the stepsizes $h_n = h$ are constant, or
(b) the stepsizes verify $h_n \geq \sigma h_{n-1}$, $2 \leq n \leq N$, for some $\sigma > 0$.

Then there exist constants $h^* > 0$, $\varrho_0 > 0$ and $C > 0$ such that the backward Euler solution $u_n$ exists for stepsizes satisfying $0 < h_n \leq h^*$ and for initial values $u_0$ with $\|u_0 - u(0)\|_D \leq \varrho_0$, as long as $t_n \leq T$. Further, we have the error bounds

$$
\|e\|_{D,\alpha} \leq C \left( \|e_0\|_D + h\|u''\|_{C_{alpha}^N([0,T], X)} \right)
$$

for constant stepsizes, and

$$
\|e\|_{D,\alpha} \leq C \left( \|e_0\|_D + \max_{1 \leq m \leq n} \left( (h_{m-1}^{1-\alpha} + h_{m+1}^{1-\alpha})M_n + h_m^{1-\alpha}M_{m,n} \right) \right)
$$

(3.12)

with

$$
M_n = \|u''\|_{L^\infty([t_{n-1}, t_n], X)}, \quad M_{m,n} = \sup_{t_{m-1} < s < t \leq t_n} \frac{\|u''(t) - u''(s)\|}{(t-s)^{\alpha}} s^{\alpha}
$$

for variable stepsizes, respectively. The constant $C$ depends on $\alpha$, $T$ and on $C_5$ of Lemma 5.5. For variable stepsizes, it further depends on $\sigma$. 

Proof. Set \( g_1 = \|u - u(0)\|_{L^\infty([0,T];D)} \) and choose \( g_1 < \varrho \leq R \) such that
\[
C_3 C_5 (2 \varrho + \|u\|_{C^0([0,T];D)}) < 1.
\]

In the first part of the proof we show the validity of the error estimates (3.12) and (3.13) under the assumptions that the numerical solution \((u_n)_{n=1}^N\) is defined as long as \( t_N \leq T \) and that
\[
\|u_n - u(0)\|_D \leq \varrho, \quad n \leq N.
\]
In the second part we justify these assumptions.

(i) In view of (3.10) and Lemma 5.5, we have to estimate \( \|d_n\|_\alpha \). Taylor series expansion shows that the defects are given by
\[
d_n = h_n \int_0^1 \tau u''(t_n - \tau h_n) \, d\tau.
\]
This immediately yields
\[
\mu(d) \leq 1/2 \max_{1 \leq n \leq N} h_n M_n.
\]

For estimating \( \lambda_{D,\alpha}(d) \) we first write for \( m < n \)
\[
d_n - d_m = h_n \int_0^1 \tau (u''(t_n - \tau h_n) - u''(t_m - \tau h_m)) \, d\tau + (h_n - h_m) \int_0^1 \tau u''(t_n - \tau h_n) \, d\tau.
\]
For constant stepsizes the second term in (3.15) drops and the estimate
\[
\frac{\|d_n - d_m\|}{(t_n - t_m)^\alpha} \leq h M_m, n \int_0^1 \tau \left( \frac{m}{m - \tau} \right)^\alpha \, d\tau \leq \frac{M_{m,n}}{1 - \alpha} h
\]
proves the first part of the theorem.

For variable stepsizes, one has
\[
\frac{\|d_n - d_m\|}{(t_n - t_m)^\alpha} \leq h M_{m,n} \left( \frac{t_n - t_m + h_m}{t_n - t_m} \right)^\alpha \int_0^1 \tau \left( \frac{t_n}{t_m - \tau h_m} \right)^\alpha \, d\tau + \frac{|h_n - h_m|}{(t_n - t_m)^\alpha} \frac{M_n}{2}.
\]
Due to our assumptions on the stepsize sequence, we have
\[
\left( \frac{t_n - t_m + h_m}{t_n - t_m} \right)^\alpha \leq \left( 1 + \frac{1}{\sigma} \right)^\alpha
\]
and
\[
\frac{|h_n - h_m|}{(t_n - t_m)^\alpha} \leq \left( h^{1-\alpha} + \frac{1}{\sigma} h^{1-\alpha} \right) T^\alpha.
\]
The remaining term in (3.16) is bounded as follows:
\[
h_m \int_0^1 \tau \left( \frac{t_n}{t_m - \tau h_m} \right)^\alpha \, d\tau \leq h_m^{1-\alpha} T^\alpha \int_0^1 \tau \left( \frac{h_m}{t_m - \tau h_m} \right)^\alpha \, d\tau \leq \frac{h_m^{1-\alpha} T^\alpha}{1 - \alpha}.
\]
Inserting these bounds into (3.16) gives the required bound for \( \lambda_\alpha(d) \).

(ii) It remains to show that the backward Euler solution exists and that (3.14) holds. The idea of the proof is simple and standard for nonlinear equations: as long as \( u_{n-1} \) remains sufficiently close to \( \bar{u}_{n-1} \), (3.3) can be solved for \( u_n \) and the above error estimate ensures that \( u_n \) is close enough to \( \bar{u}_n \) as well. Repeating this
process proves the desired result. However, we have to pay some attention to the
parameters involved.

For simplicity, we give the proof for constant stepsizes only. Set \( \varrho_2 = \varrho - \varrho_1 \), and
let \( 0 < \varrho_1 < \varrho \leq \varrho_2 \) and \( h^* \leq h \) denote the thresholds provided by Lemma 5.2
applied to \( \varrho_2 \) and \( u^* \), where \( u^* \) varies in the compact set formed by the values \( u(t) \),
\( 0 \leq t \leq T \). After a possible reduction of \( h^* \), we can choose \( \varrho_1 > 0 \) such that
\[
C(\varrho_1 + h^*)\|u''\|_{C^2(\{0,T\},X)} \leq \varrho_1/2,
\]
where \( C \) is the constant from (3.12). Since \( u \) is uniformly continuous, we can further assume that \( \|u(t_n) - u(t_{n-1})\|_D \leq \varrho_1/2 \) for \( h \leq h^* \).

Suppose by induction that \( u_n \) exists and that (3.14) is satisfied for \( n \leq m \). Then,
due to (3.12) and the above choice of parameters, the bound
\[
\|e_m\|_D \leq C\left(\|e_0\|_D + h\|u''\|_{C^2(\{0,T\},X)}\right) \leq \varrho_1/2
\]
implies
\[
\|u_m - \bar{u}_{m+1}\|_D \leq \|e_m\|_D + \|\bar{u}_m - \bar{u}_{m+1}\|_D \leq \varrho_1.
\]
An application of Lemma 5.2 with \( u^* = \bar{u}_{m+1} \) and \( w = u_m \) shows that \( u_{m+1} \) exists
and \( \|e_{m+1}\|_D \leq \varrho_1 \). Consequently, the estimate
\[
\|u_{m+1} - u(0)\|_D \leq \|e_{m+1}\|_D + \|\bar{u}_{m+1} - u(0)\|_D \leq \varrho_2 + (\varrho - \varrho_2) = \varrho
\]
follows. This yields (3.14) and concludes the proof.

In practice it might be difficult to know whether \( u'' \) belongs to \( C^2(\{0,T\},X) \). This limitation is overcome in the next theorem where we impose the natural condi-
tion
\[
Au(0) + f(u(0)) \in X_\beta,
\]
for some \( \alpha < \beta \leq 1 \). Note that, in actual applications, \( X_\beta \) is often a Sobolev space
that does not depend on the boundary conditions for \( \beta \) sufficiently small. Hence, if the
initial value is sufficiently smooth, this condition is easily seen to be satisfied.

It is also known that under (3.17) the exact solution of (2.1) has the additional
regularity properties \( u' \in L^\infty([0,T],X_\beta) \cap C^\beta([0,T],X) \) (see [12, Theorem 8.1.3]).

**Theorem 3.2.** Let \( u : [0,T] \to D \) be a solution of (2.1) such that (3.11) \( \) is satisfied and assume that (3.17) holds for some \( 0 < \alpha < \beta \leq 1 \).

Then there exist constants \( h^* > 0 \), \( \varrho_0 > 0 \) and \( C > 0 \) such that, for arbitrary
stepsizes \( 0 < h_n \leq h^* \) and for initial values \( u_0 \) with \( \|u_0 - u(0)\|_D \leq \varrho_0 \), the backward Euler solution \( u_n \) is defined as long as \( t_n \leq T \) and we have
\[
\|e\|_{D,\alpha} \leq C\left(\|e_0\|_D + \max_{1 \leq n \leq N} h_n^{3-\alpha} I_n^{\alpha/\beta} J_n^{1-\alpha/\beta}\right)
\]
with
\[
I_n = \|u'|_{L^\infty([t_{n-1},t_n],X_\beta)} \quad J_n = \|u''|_{C^\beta([t_{n-1},t_n],X)},
\]
The constant \( C \) depends on \( \alpha, \beta, T \) and on \( C_0 \) of Lemma 5.6.

**Proof.** We follow the arguments of the proof of Theorem 3.1. Therefore, it is suf-
ficient to establish the validity of (3.18) under the assumptions that the numerical
solution \( (u_n)_{n=1}^N \) exists as long as \( t_N \leq T \) and that (3.9) holds for some \( \varrho \leq R \).
In view of 3.10 and Lemma 5.1, we have to estimate \( \mu_\alpha(d) \). For the defects \( d_n \), we use the representation
\[
d_n = \int_0^1 (u'(t_n - \tau h_n) - u'(t_n)) \, d\tau
\]
to obtain the estimates
\[
\|d_n\| \leq \frac{h_n^\beta}{1 + \beta} I_n \leq h_n^\beta J_n \quad \text{and} \quad \|d_n\|_\beta \leq 2I_n.
\]
By a standard interpolation argument
\[
\|d_n\|_\alpha \leq \|d_n\|^{1-\alpha/\beta}\|d_n\|_{\beta}^{\alpha/\beta},
\]
we get
\[
\mu_\alpha(d) \leq 2 \max_{1 \leq n \leq N} (h_n^{\beta-\alpha} I_n^{\alpha/\beta} J_n^{1-\alpha/\beta}),
\]
which yields the desired result. \( \square \)

The previous theorems are local in nature. By applying them recursively, we obtain pointwise convergence estimates in \( D \) for finite times. In the following theorem, the number \( \alpha \) has the same meaning as in the local results before.

**Theorem 3.3.** Let \( u : [0, T] \to D \) be a solution of (2.1) and let \( 0 < \alpha < 1 \). Assume that either
\begin{enumerate}[(a)]
\item \( u'' \in C^0(0, T], X \) and the stepsizes \( h_n = h \) are constant, or
\item \( u'' \in C^0(0, T], X \) and \( h_n \geq \sigma h_{n-1} \), \( 2 \leq n \leq N \), for some \( \sigma > 0 \), or
\item \( Au(0) + f(u(0)) \in X_\beta \) for some \( 0 < \alpha < \beta \leq 1 \).
\end{enumerate}
Then there exist constants \( h^* > 0 \), \( \delta > 0 \) and \( C > 0 \) such that the backward Euler solution \( u_n \) exists for stepsizes satisfying \( 0 < h_n \leq h^* \) and for initial values \( u_0 \) with \( \|u_0 - u(0)\|_D \leq \delta \), as long as \( t_n \leq T \). For \( 0 \leq n \leq N \), we have the error bounds
\begin{enumerate}[(a)]
\item \( \|e_n\|_D \leq C \left( \|e_0\|_D + h \|u''\|_{C^0(0, T], X)} \right), \) or
\item \( \|e_n\|_D \leq C \left( \|e_0\|_D + \max_{1 \leq m \leq k \leq N} \left( (h_{k-1}^{1-\alpha} + h_{m+1}^{1-\alpha}) M_k + h_m^{1-\alpha} M_{m,k} \right) \right), \) or
\item \( \|e_n\|_D \leq C \left( \|e_0\|_D + \max_{1 \leq m \leq N} h_{m}^{\beta-\alpha} I_m^{\alpha/\beta} J_m^{1-\alpha/\beta} \right), \)
\end{enumerate}
respectively.

**Proof.** We only give the proof of the first result. The remaining statements follow in a similar way.

Since \( u \) is continuous, there are constants \( R > 0 \) and \( L > 0 \) such that (2.2) is uniformly satisfied for \( u^* \) varying in the set formed by the values \( u(t) \), \( 0 \leq t \leq T \). Moreover, by Lemma 5.8, there exists a partition \( 0 = T_0 < T_1 < \cdots < T_J = T \) of \([0, T]\) such that
\[
C_3 C_5 \left( 2\|u_{T_j} - u(T_j-1)\|_{L^\infty([0, H_j], D)} + \|u_{T_j}\|_{C^2([0, H_j], D)} \right) < 1, \quad 1 \leq j \leq J,
\]
with \( H_j = T_j - T_{j-1} \) and \( u_{T_j}(t) = u(T_{j-1} + t), 0 \leq t \leq H_j \). Here \( C_3 \) and \( C_5 \) are the constants provided by Lemmas 5.3 and 5.5 for \( u^* = u(T_j) \) and \( R \). Notice that these constants only depend on \( R \) and \( L \).
Therefore, we deduce from Theorem 3.1 applied piece-by-piece, that there exist positive constants \( h^* \) and \( C \), such that for \( 0 < h \leq h^* \)

\[ \|e_n\|_D \leq C \|e_0\|_D + \bar{C} h \|v''\|_{C^0((0,T_j],X)}, \quad 0 \leq t_n \leq T_j. \]

After a possible reduction of \( \delta \) and \( h^* \), this estimate shows that \( k_{\epsilon n} D = 0 \), with \( \epsilon_0 \) given by Theorem 3.1. Notice that \( J \) is independent of \( 0 < h \leq h^* \). The desired error estimate thus follows by recursion.

4. Behaviour near an asymptotically stable equilibrium

In this section we study the long-term behaviour of time discretizations of (2.1). To keep our exposition in a reasonable length, we restrict our attention to hyperbolic equilibria. For these the principle of linearized stability holds, which means that the dynamical behaviour near such an equilibrium \( u \) is fully determined by the linearized equation

\[ v' = F'(\overline{u})(v - \overline{u}) \]

(see [12 Section 9.1]). We show that a similar property holds for the backward Euler discretization of (2.1). Further, numerical simulations that illustrate our theoretical result are given.

For notational simplicity, we concentrate on the asymptotically stable case. Let \( \overline{u} \in D \) be an equilibrium of (2.1), i.e., \( F(\overline{u}) = 0 \), and assume that the sectorial operator

(4.1) \[ A = F'(\overline{u}) \]

is asymptotically stable, i.e., \( \omega_0 < 0 \).

The number \( \omega_0 \) is defined in (2.3) (see also Figure 1). In this situation, it is well known that \( \overline{u} \) is asymptotically stable and attracts all solutions in a sufficiently small neighbourhood of \( \overline{u} \) with exponential speed. More precisely, it is shown in [12 Theorem 9.1.2] that for each \( \omega < |\omega_0| \) there are constants \( \delta_0 > 0 \) and \( C > 0 \) such that the solution of (2.1) exists for all positive times and satisfies

(4.2) \[ \|u(t) - \overline{u}\|_D \leq C \cdot e^{-\omega t}\|u(0) - \overline{u}\|_D, \quad \text{for all } t \geq 0, \]

whenever the initial value satisfies \( \|u(0) - \overline{u}\|_D \leq \delta_0 \).

The following theorem gives the corresponding result for the backward Euler discretization. Note that any equilibrium of (2.1) is also an equilibrium of the backward Euler discretization.

**Theorem 4.1.** Let \( \overline{u} \) be an equilibrium of (2.1) and assume that (4.1) holds. Then, for any choice of \( \omega < |\omega_0| \), there are positive constants \( \overline{H}, \delta \) and \( C \) such that the following holds. The backward Euler solution \((u_n)_{n=1}^\infty\) of (2.1) exists for all stepsize sequences satisfying \( 0 < h_n \leq \overline{H} \) and for all initial values \( u_0 \) with \( \|u_0 - \overline{u}\|_D \leq \delta \), and we have

(4.3) \[ \|u_n - \overline{u}\|_D \leq C \cdot e^{-\omega t_n}\|u_0 - \overline{u}\|_D, \quad \text{for all } n \geq 0. \]

Note that the constant \( C \) depends on \( \omega \), but not on the particular choice of the stepsize sequence.

Demanding that the numerical solution decays towards the equilibrium nearly as fast as the exact solution imposes a severe restriction on the maximal stepsize. This restriction is overcome in the following theorem, where exponentially fast convergence is obtained, if the stepsizes remain bounded.
Theorem 4.2. Let \( \overline{v} \) be an equilibrium of (2.1) and assume that (4.1) holds. Then, for any \( \overline{h} > 0 \), there are constants \( 0 < \omega < |\omega_0|, \delta > 0 \) and \( C > 0 \) such that the backward Euler solution \( (u_n)_{n=1}^{\infty} \) of (2.1) exists for all stepsize sequences satisfying \( 0 < h_n \leq \overline{h} \) and for all initial values \( u_0 \) with \( ||u_0 - \overline{v}||_D \leq \delta \), and (4.3) holds.

Proof of Theorem 4.1. We linearize (2.1) around the equilibrium \( \overline{v} \) and construct the backward Euler solution by fixed-point iteration. In order to capture the decaying behaviour of the solution we use exponentially weighted norms. For the backward Euler solution by fixed-point iteration. In order to capture the decaying behaviour of the solution we use exponentially weighted norms. For \( \omega > 0 \) and sequences \( v = (v_n)_{n=1}^{\infty} \) in \( D \), we modify (2.8a) in the following way:

\[
\|v\|_{D, \alpha, \omega} = \mu_{D, \omega}(v) \|v\|_D, \quad \lambda_{D, \alpha, \omega}(v) = \sup_{1 \leq k < n < \infty} e^{\omega t_k} \|v_n - v_k\|_D \frac{\rho}{(t_n - t_k)^{\alpha}},
\]

as well as the corresponding norm \( \|\cdot\|_{\alpha, \omega} \) based on \( \|\cdot\| \). A crucial observation is that Lemmas 5.3 and 5.4 have an extension to these exponentially weighted norms for \( 0 < \omega < |\omega_1| < |\omega_0| \) with \( \omega_1 \) as in Lemma 5.1. The gap \( \omega - |\omega_1| \) is needed to bound the powers of \( t_n \) that are encountered.

With these preparations, we are ready to give the proof. Let \( B \) denote the ball

\[
B = \{ v \in D^\infty : \|v - \overline{v}\|_{D, \alpha, \omega} \leq g \}.
\]

We define \( \Phi \) as in (4.2a) with \( N = \infty \). Using the above-mentioned extensions of Lemmas 5.3 and 5.4 with \( u^* = \overline{v} \) proves

\[
\|\Phi(v) - \Phi(w)\|_{D, \alpha, \omega} \leq 3gC_3C_5\|v - w\|_{D, \alpha, \omega}
\]

for \( v, w \in B \). This shows that \( \Phi \) is a contraction on \( B \) with contraction factor \( 1/2 \) for \( g \) sufficiently small.

It remains to show that \( \Phi \) maps \( B \) onto \( B \) if \( u_0 \) lies sufficiently close to \( \overline{v} \). Since \( \Phi(\overline{v}) = ru_0 + (1 - r)\overline{v} \), we have for all \( v \in B \)

\[
\|\Phi(v) - \overline{v}\|_{D, \alpha, \omega} \leq \|\Phi(v) - \Phi(\overline{v})\|_{D, \alpha, \omega} + \|\Phi(\overline{v}) - \overline{v}\|_{D, \alpha, \omega} \leq 1/2 \|v - \overline{v}\|_{D, \alpha, \omega} + \|ru_0 - \overline{v}\|_{D, \alpha, \omega}.
\]

The last term is estimated by the first part of Lemma 5.3

\[
\|ru_0 - \overline{v}\|_{D, \alpha, \omega} \leq C_4\|ru_0 - \overline{v}\|_D.
\]

For \( \delta \) satisfying \( 2\delta C_4 \leq g \), we thus have \( \Phi(B) \subset B \).

This proves the existence of a unique fixed-point \( u \), which is the searched backward Euler solution. Using further

\[
\|\Phi(u) - \overline{v}\|_{D, \alpha, \omega} \leq 1/2 \|\Phi(u) - \overline{v}\|_{D, \alpha, \omega} + \|ru_0 - \overline{v}\|_{D, \alpha, \omega} \]

yields

\[
\|u - \overline{v}\|_{D, \alpha, \omega} \leq 2C_4\|ru_0 - \overline{v}\|_D.
\]

In particular, we get

\[
\sup_{1 \leq n < \infty} e^{\omega t_n} \|u_n - \overline{v}\|_D \leq 2C_4\|ru_0 - \overline{v}\|_D,
\]

which proves the assertion of the theorem. \( \square \)

Proof of Theorem 4.2. The proof is very similar to the preceding one and therefore omitted. It relies on the stability bounds given in Lemma 5.1 part (b). \( \square \)
Table 1. Numerically observed contraction factors

<table>
<thead>
<tr>
<th>h</th>
<th>1.0000</th>
<th>0.5000</th>
<th>0.2500</th>
<th>0.1250</th>
<th>0.0625</th>
<th>0.03125</th>
</tr>
</thead>
<tbody>
<tr>
<td>\omega_h</td>
<td>0.4055</td>
<td>0.4463</td>
<td>0.4711</td>
<td>0.4849</td>
<td>0.4922</td>
<td>0.4960</td>
</tr>
</tbody>
</table>

We close this section with a numerical example that illustrates Theorem 4.1.

**Example 4.3** (Combustion of a solid fuel). We take up Example 2.2 and specify the functions \( k, \varphi \) and \( U_0 \) as follows:

\[ k(y) = y^2 + 1, \quad \varphi(y) = -y(y - 1/2)(y - 1), \quad U_0(x) = 1/2 + 2x^2(1 - x)^2. \]

Note that the initial condition \( U_0 \) is compatible with the boundary conditions and that \( k \) satisfies the ellipticity condition (2.5) with \( \kappa = 1 \). The problem has three equilibria \( \overline{\pi} = 1, \overline{\pi} = 0, \) and \( \overline{\pi} = 1/2 \). The first two are asymptotically stable with \( \omega_0 = -1/2 \). Due to our choice of \( U_0 \), we expect convergence to \( \overline{\pi} = 1 \).

The partial differential equation (2.4) is discretized in space by standard finite differences on an equidistant grid with meshwidth 1/200 and in time by the backward Euler method with constant stepsize \( h \). For different values of \( h \), the integration is performed up to \( t = 40 \). The numerical approximations \( \omega_k \) to \( \omega \) are displayed in Table 1. The results are in complete agreement with Theorem 4.1.

5. Lemmas

In this section we collect the auxiliary results that are needed in the proofs of the previous theorems. Throughout the section we set

\[ (5.1) \quad f(u) = F(u) - Au, \quad \text{where} \quad A = F'(u^*) \]

for some \( u^* \in D \) and denote by \( \omega_0 \in \mathbb{R} \) the constant from (2.3) that corresponds to \( u^* \). We fix \( \kappa > \omega_0 \) and \( \overline{\kappa} > 0 \) such that \( \overline{\kappa} \omega_0 < 1 \) and consider arbitrary grid points \( 0 = t_0 < t_1 < \cdots < t_N \) that satisfy \( h_n = t_n - t_{n-1} \leq \overline{\kappa} \). There is no restriction on the maximal stepsize for \( \omega_0 \leq 0 \).

For the discrete transition operators (2.3), we have the following stability bounds.

**Lemma 5.1.** (a) For any \( \omega_1 > \omega_0 \) there exist constants \( h^* > 0 \) and \( C_1 > 0 \) such that for \( 0 \leq \nu \leq 1 \)

\[ (5.2) \quad \| (\kappa - A)^\nu r(t_n, t_k) \|_{X \rightarrow X} \leq C_1 \frac{e^{\omega_1(t_n-t_k)}}{(t_n-t_k)^\nu}, \quad 0 \leq k < n, \]

whenever the stepsizes are bounded by \( h^* \).

(b) Let \( \omega_0 < 0 \) and \( h^* > 0 \). Then there exist constants \( \omega_1 < \omega_0 < 0 \) and \( C_1 > 0 \) such that (5.2) holds, whenever the stepsizes are bounded by \( h^* \).

Similar bounds are given in [2] [4] [14]. We note for later use that (5.2) also holds for \( 1 \leq \nu \leq 2 \) if \( k \leq n - 1 \).

**Proof.** The estimate (5.2) is a consequence of the stability bounds

\[ \| e^{tA} \|_{X \rightarrow X} \leq C e^{\omega_0 t}, \quad \| A e^{tA} \|_{X \rightarrow X} \leq C \frac{e^{\omega_0 t}}{t}, \quad t > 0, \]

for the analytic semigroup. Using the representation

\[ r(t_n, t_k) = \int_0^\infty \cdots \int_0^\infty e^{-s_{k+1} - \cdots - s_n} e^{(s_{k+1} h_{k+1} + \cdots + s_n h_n)A} ds_{k+1} \cdots ds_n \]
shows
\[ \|r(t_n, t_k)\|_{X \to X} \leq C \prod_{j=k+1}^{n} (1 - h_j \omega_0)^{-1}, \]
\[ \|Ar(t_n, t_k)\|_{X \to X} \leq C \int_{-\infty}^{\omega_0} \prod_{j=k+1}^{n} (1 - h_j \omega)^{-1} d\omega. \]

For \( \omega \leq \omega_0 \leq 0 \), we have
\[ 1 - h_j \omega \geq (1 - h_j \omega_0)(1 + ch_j(\omega_0 - \omega)) \]
with \( c = 1 - h^* \omega_0 \). Arguing as in [4] shows
\[ \|Ar(t_n, t_k)\|_{X \to X} \leq C \frac{1 - h^* \omega_0}{t_n - t_k} \prod_{j=k+1}^{n} (1 - h_j \omega_0)^{-1}. \]

For \( \omega_0 > 0 \) we use an idea from [6] and eliminate the small steps by
\[ (1 - h_j \omega)(1 - h_k \omega) \geq 1 - (h_j + h_k)\omega, \]
until (5.3) is again satisfied. Part (a) of the lemma then follows from standard estimates and interpolation.

In order to verify (b) we note that the function
\[ \omega_1 = \omega_1(H) = \frac{\log(1 - H\omega_0)}{H} \]
is monotonically increasing for \( \omega_0 < 0 \) with \( \omega_1(0) = \omega_0 \) and \( \omega_1(\infty) = 0 \). Hence,
\[ (1 - h_j \omega_0)^{-1} \leq e^{\omega_1 h_j} \]
with \( \omega_1 \) given by (5.4) for \( H = \max h_j \leq h^* \).

We note for later use that the identity
\[ r(t_n, t_k) - 1 = \sum_{l=k+1}^{n} h_l Ar(t_n, t_{l-1}) \]
together with Lemma 5.1 implies for \( 0 \leq k < n \leq N \) and \( 0 < \nu \leq 1 \) the bound
\[ \|(r(t_n, t_k) - 1)(\kappa - A)^{-\nu}\|_{X \to X} \leq C \frac{1}{\nu} e^{\omega_1^+(t_n - t_k)} (t_n - t_k)^\nu \]
with \( \omega_1^+ = \max(\omega_1, 0) \). For simplicity, we make no notational difference between the constants in (5.2) and (5.5).

**Lemma 5.2.** Let \( u^* \in D \) and \( R_0 > 0 \). Then there exist \( 0 < \rho_* < q^* \leq R_0 \) and \( h^* > 0 \) such that, for \( w \in D \) with \( \|w - u^*\|_{D} \leq \rho_* \) and for \( 0 < h \leq h^* \), the equation
\[ \frac{v - w}{h} = Av + f(v) \]
possesses a unique solution \( v \in D \) with \( \|v - u^*\|_{D} \leq \rho^* \). Moreover, the quantities \( \rho_* \), \( q^* \) and \( h^* \) can be chosen uniformly for \( u^* \) belonging to a relatively compact subset of \( D \).

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Proof. We first note that, due to (2.2), there exist $R > 0$ and $L > 0$ such that
\begin{equation}
\|f'(v) - f'(w)\|_{D \to X} \leq L\|v - w\|_D,
\end{equation}
for all $v, w \in D$ with $\|v - u^*\|_D \leq R$ and $\|w - u^*\|_D \leq R$. Therefore, since $f'(u^*) = 0$, we also have
\begin{equation}
\|f'(v)\|_{D \to X} \leq L\theta,
\end{equation}
for all $v \in D$ such that $\|v - u^*\|_D \leq \theta \leq R$. This implies that
\begin{equation}
\|f(v) - f(w)\| \leq L\theta \|v - w\|_D,
\end{equation}
for all $v, w \in D$ with $\|v - u^*\|_D \leq \theta \leq R$ and $\|w - u^*\|_D \leq \theta \leq R$.

Equation (5.6) is equivalent to $v = g(v)$, where $g$ is defined by
\begin{equation*}
g(v) = (1 - hA)^{-1}w + h(1 - hA)^{-1}f(v).
\end{equation*}
We solve (5.6) by fixed-point iteration in the set $B = \{v \in D : \|v - u^*\|_D \leq \varrho^*\}$. For this, we have to show that $g$ is contractive and maps $B$ onto $B$, for $\varrho^*$ sufficiently small.

By the equivalence of $\|\cdot\|_D$ with the graph-norm of $A$, there exists $\overline{M}$ such that
\begin{equation*}
\|h(1 - hA)^{-1}\|_{X \to D} \leq \overline{M}, \quad \|(1 - hA)^{-1}\|_{D \to D} \leq \overline{M}
\end{equation*}
for $0 < h \leq \overline{h}$.

On the one hand, we have
\begin{equation*}
\|g(v) - g(v)\|_D \leq \overline{M}L\varrho^*\|v - \overline{v}\|_D,
\end{equation*}
for $h \leq \overline{h}$ and $v, \overline{v} \in D$ with $\|v - u^*\|_D \leq \varrho^*$ and $\|\overline{v} - u^*\|_D \leq \varrho^*$. On the other hand, it holds
\begin{equation*}
g(v) - u^* = (1 - hA)^{-1}(w - u^*) + h(1 - hA)^{-1}(Au^* + f(u^*))
\end{equation*}
\begin{equation*}
+ h(1 - hA)^{-1}(f(v) - f(u^*)),
\end{equation*}
so that
\begin{equation*}
\|g(v) - u^*\|_D \leq \overline{M}\|w - u^*\|_D + \|h(1 - hA)^{-1}(Au^* + f(u^*))\| + \overline{M}L\varrho^*\|v - u^*\|_D.
\end{equation*}

In view of these bounds, if we choose $\varrho^*$ and $\varrho^*$ such that $\overline{M}\varrho^* \leq \varrho^*/3$ and $\overline{M}L\varrho^* \leq 1/3$, then $g$ is a contraction on $B$. Moreover, since $h(1 - hA)^{-1} \to 0$ strongly as an operator from $X$ to $D$, we can select $h^* \leq \overline{h}$ such that, for $0 < h \leq h^*$,
\begin{equation*}
\|h(1 - hA)^{-1}(Au^* + f(u^*))\|_D \leq \varrho^*/3.
\end{equation*}

Thus, $g$ maps $B$ into $B$, and the fixed-point theorem provides the existence of a unique solution $v$ of (5.3).

Since $F'$ is locally Lipschitz continuous, $R_0$ and $L$ can be taken uniformly for $u^*$ in a compact set. Moreover, the equivalence of $\|\cdot\|_D$ with the graph-norm of $F'(u^*)$ is also uniform on the compact set. With this, the statement of the lemma follows easily.

**Lemma 5.3.** For $0 < \alpha < 1$ there exist constants $C_3 > 0$ and $R > 0$ such that
\begin{equation}
\|f(v) - f(w)\|_\alpha \leq C_3 \left(2\varrho + \lambda_{D,\alpha}(w)\right)\|v - w\|_{D,\alpha}
\end{equation}
for all $v$ and $w$ in the set $V = \{\overline{v} \in D^N : \mu_D(\overline{v} - u^*) \leq \varrho\}$ whenever $0 < \varrho \leq R$. 

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Due to (5.7), the remaining term can be bounded as follows:

\[ (f(v) - f(w)) - (f(v_m) - f(w_m)) = \int_0^1 (G_n(v_n - w_n) - G_m(v_m - w_m)) \, d\sigma \]

\[ = \int_0^1 G_n((v_n - w_n) - (v_m - w_m)) \, d\sigma + \int_0^1 (G_n - G_m) (v_m - w_m) \, d\sigma. \]

Using (5.8), we can estimate the first term on the right-hand side by

\[ \int_0^1 \| G_n((v_n - w_n) - (v_m - w_m)) \| \, d\sigma \leq \| G_n - G_m \|_{D} (t_n - t_m)^{\alpha} t_m^{-\alpha}. \]

Due to (5.1), the remaining term can be bounded as follows:

\[ \int_0^1 \| (G_n - G_m) (v_m - w_m) \| \, d\sigma \]

\[ \leq L \int_0^1 \| w_n - w_m \|_{D} + \| (v_n - w_n) - (v_m - w_m) \|_{D} \| v_m - w_m \|_{D} \]

\[ \leq L (\lambda_{D,\alpha}(w) + 1/2 \lambda_{D,\alpha}(v - w)) \mu_D(v - w)(t_n - t_m)^{\alpha} t_m^{-\alpha}. \]

The above estimates readily give

\[ \lambda_{\alpha}(f(v) - f(w)) \leq L \left( 2\mu_{D,\alpha}(v - w) + \lambda_{D,\alpha}(w) \mu_D(v - w) \right), \]

and this inequality combined with (5.11) proves (5.10).

Proof. Choose \( R \) as in (2.2) and let \( v, w \in V \) for some \( 0 < q \leq R \). In view of (5.9), we have

\[ \mu(f(v) - f(w)) \leq Lq \mu_D(v - w), \]

and thus it remains to bound \( \lambda_{\alpha}(f(v) - f(w)) \). We set \( G_n = f'(\sigma v_n + (1 - \sigma)w_n) \), \( 0 \leq \sigma \leq 1 \), and write for \( m < n \)

\[ (f(v) - f(w)) - (f(v_m) - f(w_m)) = \int_0^1 (G_n(v_n - w_n) - G_m(v_m - w_m)) \, d\sigma \]

\[ = \int_0^1 G_n((v_n - w_n) - (v_m - w_m)) \, d\sigma + \int_0^1 (G_n - G_m) (v_m - w_m) \, d\sigma. \]

In Lemmas 5.4, 5.5 and 5.6 below we establish certain estimates involving \( \| \cdot \|_{D,\alpha} \).

As \( \| \cdot \|_{D} \) is equivalent to the graph-norm of \( A \), the norm

\[ \| v \|_{\alpha} + \| Av \|_{\alpha}, \quad v \in D^N, \]

is equivalent to \( \| \cdot \|_{D,\alpha} \) as well, for all \( 0 < \alpha < 1 \). Since the required estimates for \( \| \cdot \|_{\alpha} \) are usually obtained more easily (and in a similar way) than the corresponding estimates for \( \| A \cdot \|_{\alpha} \), we give for simplicity the proofs only for \( \| A \cdot \|_{\alpha} \). Henceforth, \( C \) denotes a generic constant that possibly depends on \( C_1 \) and on constants that arise from changing between equivalent norms.

**Lemma 5.4.** Let \( 0 < \alpha < 1 \).

(a) There exists a constant \( C_4 > 0 \) such that for every \( v \in D \)

\[ \| rv \|_{D,\alpha} \leq C_4 \| v \|_{D}. \]

The constant \( C_4 \) depends on \( t_N \), but it is otherwise independent of the grid. If \( \omega_0 \) is nonnegative, then \( C_4 \) is bounded for finite times. If \( \omega_0 \) is negative, then \( C_4 \) can be chosen independently of \( t_N \).

(b) For \( x \in X \) we have

\[ \lim_{t_N \to 0} \| (r - 1) x \|_{\alpha} = 0. \]

The convergence is uniform on relatively compact subsets of \( X \).
Proof. In order to prove the first statement of the lemma, we have to estimate $A(r(t_n, 0) - r(t_m, 0)) v$. Using the identity

$$r(t_n, 0) - r(t_m, 0) = (r(t_n, t_m) - 1) r(t_m, 0)$$

we obtain

$$\|A(r(t_n, 0) - r(t_m, 0)) v\| \leq C \|(r(t_n, t_m) - 1)(\kappa - A)^{-\alpha}\|_X \times \|A(\kappa - A)^\alpha r(t_m, 0)\|_X \|v\|_D.$$ 

With the help of (5.2) and (5.5) the right-hand side can be bounded by

$$\frac{C}{\alpha} \, e^{\omega_1 t_N} \|v\|_D (t_n - t_m)^{\alpha - \alpha},$$

which proves the first result.

To show the second statement of the lemma we choose $\bar{x} \in D$. From the identity

$$r(t_k, 0) - r(t_k-1, 0) = h_k A r(t_k, 0)$$

we get

$$\|(r(t_n, 0) - r(t_m, 0)) x\| \leq \sum_{k=m+1}^n h_k \left( \|A r(t_k, 0) (x - \bar{x})\| + \|r(t_k, 0) A \bar{x}\| \right)$$

$$\leq Ct_m^{-\alpha} \sum_{k=m+1}^n h_k t_k^{-1+\alpha} e^{\omega_1 t_k} \|x - \bar{x}\| + C \sum_{k=m+1}^n h_k e^{\omega_1 t_k} \|\bar{x}\|_D$$

$$\leq C (\|x - \bar{x}\| + t_N \|\bar{x}\|_D) e^{\omega_1 t_N} (t_n - t_m)^{\alpha} t_m^{-\alpha}.$$ 

Since $D$ is dense in $X$, the second statement of the lemma follows. 

Lemma 5.5. For $0 < \alpha < 1$ there exists a constant $C_5 > 0$ such that if $\|v\|_\alpha < \infty$ we have

$$\|\mathcal{K}(v)\|_{D, \alpha} \leq C_5 \|v\|_\alpha.$$ 

The constant $C_5$ depends on $t_N$, but it is otherwise independent of the grid. If $\omega_0$ is nonnegative, then $C_5$ is bounded for finite times. If $\omega_0$ is negative, then $C_5$ can be chosen independently of $t_N$.

Proof. Analogously to the modified variation-of-constants formula (1.3) and with the help of

$$h_k A r(t_n, t_{k-1}) = r(t_n, t_{k-1}) - r(t_n, t_k),$$

we split $\mathcal{K}(v)$ such that $A \mathcal{K}(v) = a + b$ where

$$a_n = \sum_{k=1}^n h_k A r(t_n, t_{k-1}) (v_k - v_n),$$

$$b_n = \sum_{k=1}^n h_k A r(t_n, t_{k-1}) v_n = (r(t_n, 0) - 1) v_n.$$ 

According to this we have to estimate the four terms $\mu(a), \lambda_\alpha(a), \mu(b),$ and $\lambda_\alpha(b)$.
With the help of Lemma 5.7 we get the integral in a similar way as in Lemma 5.7.

where \( B \) denotes the beta function. The last bound follows from comparing with the integral in a similar way as in Lemma 5.7.

(ii) In order to estimate \( \lambda_\alpha(a) \) we use the identity

\[
\sum_{k=m+1}^{n} h_k A r(t_n, t_{k-1})(v_k - v_n) + \sum_{k=1}^{m} h_k A r(t_n, t_{k-1})(v_m - v_n)
\]

\[
+ \sum_{k=1}^{m} h_k A \left(r(t_n, t_{k-1}) - r(t_m, t_{k-1})\right)(v_k - v_m)
\]

\[
= S_1 + S_2 + S_3.
\]

We take norms and use again (5.2) and (5.5). This gives

\[
\|S_1\| \leq C_1 e^{\omega_2 t N} \lambda_\alpha(v) \sum_{k=m+1}^{n} \frac{h_k}{(t_n - t_{k-1})^{1-\alpha t_k}}
\]

\[
\leq \alpha^{-1} C_1 e^{\omega_2 t N} \lambda_\alpha(v) (t_n - t_m)^\alpha t_m^{-\alpha},
\]

and, together with (5.12),

\[
\|S_2\| \leq \|r(t_n, t_m)(r(t_m, 0) - 1)(v_m - v_n)\|
\]

\[
\leq C_1 (1 + C_1) e^{\omega_2 t N} \lambda_\alpha(v) (t_n - t_m)^\alpha t_m^{-\alpha}.
\]

With the help of Lemma 5.7 we get

\[
\|S_3\| \leq \sum_{k=1}^{m} \sum_{l=m+1}^{n} h_k h_l \|A r(t_l, t_{k-1})(v_k - v_m)\|
\]

\[
\leq C_1 \lambda_\alpha(v) \sum_{k=1}^{m} \sum_{l=m+1}^{n} h_k h_l e^{\omega_1 (t_l - t_{k-1})} \frac{(t_m - t_k)^\alpha}{(t_l - t_{k-1})^{2 t_k}}
\]

\[
\leq \frac{4C_1}{\alpha(1-\alpha)} e^{\omega_2 t N} \lambda_\alpha(v) (t_n - t_m)^\alpha t_m^{-\alpha}
\]

which proves the estimate for \( \lambda_\alpha(a) \).

(iii) The stability bound (5.4) for the transition operator immediately gives

\[
\mu(b) \leq \left(1 + C_1 e^{\omega_2 t N}\right) \mu(v).
\]

(iv) For the estimate of \( \lambda_\alpha(b) \) we write

\[
b_n - b_m = (r(t_n, 0) - 1)v_n - (r(t_m, 0) - 1)v_m
\]

\[
= \left(r(t_n, t_m) - 1\right)(\kappa - A)^{-\alpha}(\kappa - A)^\alpha r(t_m, 0)v_n
\]

\[
+ \left(r(t_m, 0) - 1\right)(v_n - v_m).
\]

A further application of (5.2) and (5.5) yields

\[
\|b_n - b_m\| \leq \left(\frac{C_2^2}{\alpha} e^{\omega_2 t N} \mu(v) + \left(1 + C_1 e^{\omega_2 t N}\right) \lambda_\alpha(v)\right)(t_n - t_m)^\alpha t_m^{-\alpha}.
\]
This finally concludes the proof of the lemma.

The following lemma is used in the proof of Theorem 5.2. For the definition of the norm $\mu_\alpha$, we refer to (2.9).

**Lemma 5.6.** For $0 < \alpha < 1$ there exists a constant $C_6 > 0$ such that

$$\|\mathcal{K}(v)\|_{\mathcal{C}^\alpha} \leq C_6 \mu_\alpha(v) \quad \text{for } v \in \mathcal{C}^N.$$  

The constant $C_6$ depends on $t_N$, but it is otherwise independent of the grid.

**Proof.** Using (5.2) we have for $w = \mathcal{K}(v)$

$$\|w_n\|_{\mathcal{C}^\alpha} \leq C \sum_{k=1}^{\alpha} h_k \| (\kappa - A)^{1-\alpha} r(t_n, t_{k-1}) \|_{X \rightarrow X} \| (\kappa - A)^\alpha v_k \|$$

and further, by comparing the sum with the corresponding integral,

$$\mu_D(w) \leq \frac{C \mu_\alpha(v)}{\alpha} e^{\omega^\alpha t_N} \mu_\alpha(v).$$

In order to estimate $\lambda_D, (\alpha)$, we split $A(w_n - w_m) = S_1 + S_2$ where

$$S_1 = \sum_{k=m+1}^{n} h_k A r(t_n, t_{k-1}) v_k$$

and, due to $r(t_i, t_{k-1}) - r(t_i, t_{k-1}) = h_i A r(t_i, t_k)$, we get

$$S_2 = \sum_{k=1}^{m} h_k A (r(t_n, t_{k-1}) - r(t_m, t_{k-1})) v_k = \sum_{k=1}^{m} h_k \sum_{l=m+1}^{n} h_l A^2 r(t_l, t_{k-1}) v_k.$$  

As before, we premultiply $v_k$ with $(\kappa - A)^\alpha$ and use (5.2) and the corresponding integrals to estimate $S_1$ and $S_2$ by

$$\|S_1\| \leq \frac{C \mu_\alpha(v)}{\alpha} e^{\omega^\alpha t_N} (t_n - t_m)^\alpha t_m^{-\alpha},$$

$$\|S_2\| \leq \frac{C \mu_\alpha(v)}{\alpha(1 - \alpha)} e^{\omega^\alpha t_N} (t_n - t_m)^\alpha t_m^{-\alpha}.$$  

This concludes the proof of the lemma.

**Lemma 5.7.** The inequality

$$\sum_{k=1}^{m} h_k \sum_{l=m+1}^{n} h_l \frac{(t_m - t_k)^\alpha}{(t_l - t_{k-1})^2 t_k^\alpha} \leq \frac{4}{\alpha(1 - \alpha)} (t_n - t_m)^\alpha t_m^{-\alpha}$$

holds for $1 \leq m < n \leq N$.

**Proof.** By comparing with the corresponding integral, we get

$$\sum_{l=m+1}^{n} h_l \frac{h_l}{(t_l - t_{k-1})^2} \leq \frac{t_n - t_m}{(t_m - t_{k-1})(t_n - t_{k-1})} \quad \text{for } 1 \leq k \leq m.$$  

We thus have to estimate

$$(t_n - t_m) \sum_{k=1}^{m} h_k \frac{(t_m - t_k)^{1-\alpha} t_k^\alpha (t_n - t_{k-1})}{(t_m - t_{k-1})^{1-\alpha} t_k^\alpha (t_n - t_{k-1})}.$$
For this we consider the function
\[
G(s) = \frac{1}{(t_m - s)^{1-\alpha} s^\alpha (t_n - s)}, \quad 0 < s < t_m.
\]
Let \( t^* \) be the point where \( G \) attains its minimum, and let \( 1 \leq p \leq m \) be the index such that \( t_{p-1} \leq t^* \leq t_p \). We split the sum into three parts (from 1 to \( p - 1 \), the term with \( k = p \), and from \( p \) to \( m \)) and compare each part with a corresponding integral. By means of the variable change \( \sigma t_m = s \), we get
\[
(t_n - t_m) \sum_{k=1}^{m} \frac{h_k}{(t_m - t_{k-1})^{1-\alpha} t_k^n (t_n - t_{k-1})} \leq \theta \int_0^1 \frac{d\sigma}{(1-\sigma)^{1-\alpha} \sigma^\alpha (\theta + 1 - \sigma)},
\]
where \( \theta = (t_n - t_m)/t_m \). The elementary estimates
\[
\theta \int_0^{1/2} \frac{d\sigma}{(1-\sigma)^{1-\alpha} \sigma^\alpha (\theta + 1 - \sigma)} \leq \frac{2 \theta}{2\theta + 1} \frac{1}{1-\alpha} \leq \frac{2\theta^\alpha}{1-\alpha},
\]
and
\[
\theta \int_{1/2}^{1} \frac{d\sigma}{(1-\sigma)^{1-\alpha} \sigma^\alpha (\theta + 1 - \sigma)} \leq 2^\alpha \theta^\alpha \int_0^\infty \frac{d\tau}{(1+\tau)^{1-\alpha}} \leq \frac{\theta^\alpha}{\alpha} + \frac{2 \theta^\alpha}{1-\alpha},
\]
where we used \( 1 - \sigma = \theta \tau \), finally prove the lemma.

**Lemma 5.8.** Let \( u : [0, T] \to D \) be a solution of (2.1). Then, for every \( \sigma > 0 \), there exists a partition \( 0 = T_0 < T_1 < \cdots < T_J = T \) such that
\[
2 \| u_{T_j} - u(T_{j-1}) \|_{L^\infty([0,H_j], D)} + \| u_{T_j} \|_{C^0_0([0,H_j], D)} \leq \sigma, \quad 1 \leq j \leq J,
\]
where \( H_j = T_j - T_{j-1} \) and \( u_{T_j}(t) = u(T_{j-1} + t), \quad 0 \leq t \leq H_j \).

**Proof.** Choose \( R > 0 \) and \( L > 0 \) as in (2.2) for \( u^* = u(0) \). From the proof of Theorem 8.1.1 in [12], it follows that there exist constants \( C > 0 \) and \( 0 < H_1 \leq T \) such that
\[
2 \| u - u(0) \|_{L^\infty([0,H_1], D)} + \| u \|_{C^0_0([0,H_1], D)} 
\leq C \| ((e^{tA} - 1)(Au(0) + f(u(0)))) \|_{C^0_0([0,H_1], X)},
\]
The constant \( C \) depends on \( L \) and the bound is valid as long as \( \| u(t) - u(0) \|_D \leq \lambda \) for \( 0 \leq t \leq H_1 \). The right-hand side of (5.13) tends to 0 as \( H_1 \) goes to 0. Thus, after a possible reduction of \( H_1 \), we get (5.13) with \( j = 1 \). We go on with this construction, and since the constants \( L \) and \( R \) can be taken uniformly, the final time \( T \) is reached after a finite number of steps. 

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