

Single Step Galerkin Approximations for Parabolic Problems

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Abstract. In this paper we construct and analyze classes of single step methods of arbitrary order for homogeneous linear initial boundary value problems for parabolic equations with time-independent coefficients. The spatial discretization is done by means of general Galerkin-type methods.

1. Introduction. In this paper we shall consider the approximate solution of the initial boundary value problem

$$(1.1) \quad \begin{aligned} D_t u &= -Lu \equiv \sum_{j,k=1}^N \frac{\partial}{\partial x_j} \left(a_{jk} \frac{\partial u}{\partial x_k} \right) - a_0 u \quad \text{in } \Omega \times (0, t^*], \\ u(x, t) &= 0 \quad \text{on } \partial\Omega \times (0, t^*], \\ u(x, 0) &= v(x) \quad \text{for } x \in \Omega. \end{aligned}$$

Here Ω is a bounded domain in R^N with sufficiently smooth boundary $\partial\Omega$, a_{jk} and a_0 are sufficiently smooth functions which are independent of t , the matrix (a_{jk}) is symmetric and uniformly positive definite and a_0 is nonnegative on $\bar{\Omega}$. All functions considered are real valued.

In Bramble, Schatz, Thomée and Wahlbin [3] the discretization of this problem in the space variables was considered by means of Galerkin's method, using a family $\{\mathcal{S}_h\}$ of finite element spaces with certain approximation properties, thus replacing (1.1) by an approximating system of ordinary differential equations in time. Special emphasis was placed on deriving optimal order error estimates for time bounded away from zero, under weak regularity assumptions on the initial data. This pursued a point of view taken previously in Blair [1], Helfrich [8] and Thomée [12] (cf. [3] for further references on semidiscrete Galerkin methods).

In the present paper the purpose is to study discretization also of the time variable. In particular, we shall formulate single step (in time) completely discrete schemes based on the above discretization in space and prove estimates analogous to those of [3] for such schemes.

In order to describe our investigations, let $\{\lambda_j\}_1^\infty$ and $\{\varphi_j\}_1^\infty$ be the eigenvalues (in nondecreasing order) and $(L_2$ orthonormal) eigenfunctions of the operator L (with boundary values zero). For s real we let $\dot{H}^s = \dot{H}^s(\Omega)$ denote the space of functions $w \in L_2$ for which (with (\cdot, \cdot) the inner product in $L_2(\Omega)$)

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$$\|w\|_s = \left(\sum_j \lambda_j^s(w, \varphi_j)^2 \right)^{1/2} < \infty.$$

Recall that for $s \geq 0$, in order that $w \in \dot{H}^s$, it is required not only that $w \in H^s(\Omega) = W_2^s(\Omega)$ but also that certain boundary conditions be satisfied (cf. [4]). For $s = 0$ we shall normally omit the subscript and denote the norm in $L_2 = L_2(\Omega)$ by $\| \cdot \|$.

Now let T be the solution operator of the elliptic problem

$$Lw = f \quad \text{in } \Omega, \quad w = 0 \quad \text{on } \partial\Omega,$$

so that

$$Tf = \sum_j \lambda_j^{-1}(f, \varphi_j)\varphi_j.$$

This operator is a bounded operator from \dot{H}^s into \dot{H}^{s+2} . In terms of T we can write the parabolic problem (1.1) as

$$D_t T u + u = 0 \quad \text{for } 0 < t \leq t^*, \quad u(0) = v,$$

and its exact solution as

$$(1.2) \quad u(t) = \sum_j e^{-t\lambda_j}(v, \varphi_j)\varphi_j \equiv \exp(-tL)v.$$

For the purpose of discretizing this problem in space, let $\{S_h\}$ (h small and positive) be a family of finite dimensional subspaces of L_2 . As in [3] we shall assume that we are given a corresponding family of operators $T_h: L_2 \rightarrow S_h$ with the properties:

- (i) T_h is selfadjoint, positive semidefinite on L_2 and positive definite on S_h ;
- (ii) There is a positive integer $r \geq 2$ and a constant C such that

$$\|(T_h - T)v\| \leq Ch^{q+2} \|v\|_q \quad \text{for } 0 \leq q \leq r - 2,$$

or, in some cases, alternatively,

- (iib) There is a positive integer $r > 2$ and a constant C such that

$$\|(T_h - T)v\|_{-p} \leq Ch^{p+q+2} \|v\|_q \quad \text{for } 0 \leq p, q \leq r - 2.$$

We then consider the semidiscrete problem: Find $u_h(t) \in S_h$ such that

$$D_t T_h u_h(t) + u_h(t) = 0 \quad \text{for } 0 < t \leq t^*,$$

$$u_h(0) = P_0 v \in S_h,$$

where P_0 denotes the projection onto S_h in $L_2(\Omega)$. Introducing the inverse $L_h = T_h^{-1}$ of T_h on S_h , this can also be written

$$D_t u_h(t) + L_h u_h(t) = 0 \quad \text{for } 0 < t \leq t^*, \quad u_h(0) = P_0 v.$$

In analogy to (1.2), its solution admits the representation

$$(1.3) \quad u_h(t) = \sum_j e^{-t\Lambda_j}(v, \Phi_j)\Phi_j = \exp(-tL_h)P_0 v,$$

where $\{\Lambda_j\}$ and $\{\Phi_j\}$ are the eigenvalues and eigenfunctions of L_h . Notice that the

Λ_j are the inverses of the positive eigenvalues of T_h .

An important feature of this formulation is that it encompasses several different procedures for dealing with the homogeneous boundary condition (cf. [3]).

In [3], assuming (i) and (iia) above, it was first proved, by the energy method, that

$$(1.4) \quad \|u_h(t) - u(t)\| \leq Ch^s \|v\|_s, \quad 0 \leq s \leq r,$$

uniformly on $(0, t^*]$. It was then shown by means of spectral representations that

$$(1.5) \quad \|u_h(t) - u(t)\| \leq Ch^r t^{-r/2} \|v\|,$$

so that the error is in fact of optimal order in h for t bounded away from zero, even with v only in L_2 . After that, estimates also in maximum norm were derived provided such estimates were known for the stationary problem. These results thus extended to the present level of generality results known before in special cases (cf. the references in [3]). Further, particular estimates were obtained for the case in which u_h satisfies the interior equation

$$(D_t u_h, \chi) + A(u_h, \chi) = 0, \quad \forall \chi \in S_h^0(\Omega_0),$$

where $S_h^0(\Omega_0)$ denotes the elements of S_h with supports in Ω_0 and

$$(1.6) \quad A(v, w) = \int_{\Omega} \left(\sum_{j,k} a_{jk} \frac{\partial v}{\partial x_j} \frac{\partial w}{\partial x_k} + a_0 v w \right) dx,$$

and where the elements of S_h are assumed to satisfy a condition of translation invariance on Ω_0 . Specifically, it was shown that arbitrary spatial derivatives of u can be approximated to optimal order in the interior of Ω_0 by difference quotients of u_h and finally that by applying the averaging process of Bramble and Schatz [2], superconvergent $O(h^{2r-2})$ approximations can be defined provided the assumption (iib) holds.

We now turn to the purpose of the present paper, the construction and analysis of single step arbitrary order completely discrete schemes for the parabolic problem (1.1).

The discrete approximations $U^n, n = 0, 1, \dots$, to the exact solution $u(t)$ of the parabolic problem at $t = nk$, with k the step size in time, will be defined in terms of a rational approximation $r(\tau)$ to the exponential $e^{-\tau}$ by the recursion formula

$$(1.7) \quad \begin{aligned} U^{n+1} &= r(kL_h)U^n, \quad n = 0, 1, \dots, nk \leq t^*, \\ U^0 &= P_0 v. \end{aligned}$$

The rational functions employed will be assumed to satisfy, for some $\nu \geq 1$,

$$(1.8) \quad r(\tau) = e^{-\tau} + O(\tau^{\nu+1}) \quad \text{as } \tau \rightarrow 0,$$

which will signify that the accuracy in the time discretization is of order ν . In addition they will be classified according to their behavior on the positive real line. In particular, $r(k\lambda)$ will have no pole for λ an eigenvalue of L_h , so that (1.7) defines U^n uniquely as an element of S_h .

Since T_h rather than L_h is considered given, it is sometimes convenient to express $r(kL_h)$ as a rational function of T_h , or equivalently, to consider the rational function $r(k/\mu)$ of μ . Assuming that this function has the form

$$r(k/\mu) = \alpha_0 \prod_j (\mu - \beta_j) / \prod_j (\mu - \gamma_j),$$

the recursion formula (1.7) for U^n may be written

$$\prod_j (T_h - \gamma_j) U^{n+1} = \alpha_0 \prod_j (T_h - \beta_j) U^n.$$

Hence, in order to determine U^{n+1} from U^n , with T_h given, it is sufficient to solve a sequence of equations of the form

$$(1.9) \quad (\alpha T_h + \beta)W = (\gamma T_h + \delta)V,$$

for W , with V given. Here, although U^n and U^{n+1} are both real, $\alpha, \beta, \gamma, \delta$ and hence also V and W may be complex valued, with $T_h f$ defined for complex f by linearity. In applications, T_h is often defined by means of a positive definite bilinear form (cf. [3, Section 8]),

$$B_h(T_h f, \chi) = (f, \chi), \quad \forall \chi \in S_h.$$

In this case, (1.9) takes the form

$$\alpha(W, \chi) + \beta B_h(W, \chi) = \gamma(V, \chi) + \delta B_h(V, \chi), \quad \forall \chi \in S_h.$$

We will return below to convenient choices of such rational functions.

Under our different assumptions on the time discretization schemes, to which we shall return presently, we shall derive error estimates corresponding to the ones quoted above for the semidiscrete situation. The analysis relies on the fact that similarly to $u_h(t)$, U^n can be represented in terms of the discrete eigenfunctions and eigenvalues as

$$(1.10) \quad U^n = r(kL_h)^n P_0 v = \sum_j r(k\Lambda_j)^n (v, \Phi_j) \Phi_j.$$

Notice in particular that the scheme (1.7) will be stable in L_2 if $\max_j |r(k\Lambda_j)| \leq 1$; we then immediately find by Parseval's relation that

$$(1.11) \quad \|U^n\| \leq \|P_0 v\| \leq \|v\|.$$

This condition will be satisfied for all schemes employed below.

We shall now describe our estimates. In Section 2, we derive such estimates in L_2 . First we prove the analogue of (1.5) which reads

$$(1.12) \quad \|U^n - u(nk)\| \leq C(h^r t^{-r/2} + k^\nu t^{-\nu}) \|v\|, \quad 0 < t = nk \leq t^*.$$

The proof of this estimate is based on the eigenfunction expansions (1.2) and (1.3). After that we derive an analogue of (1.4) for smooth data,

$$(1.13) \quad \|U^n - u(nk)\| \leq C(h^r \|v\|_r + k^\nu \|v\|_{2\nu}).$$

In contrast to the semidiscrete case this latter estimate is now a consequence of the estimate for nonsmooth data and the following representation of smooth initial data, namely

$$v = \sum_{j=0}^{\nu-1} T_h^j (T - T_h) L^{j+1} v + T_h^\nu L^\nu v.$$

Section 2 also contains estimates for less smooth data which are uniform for small t but not of the highest order $O(h^r + k^\nu)$, as well as estimates for approximations to time derivatives.

In Section 3 we derive the analogue in the completely discrete case to the maximum norm estimates of [3]. Section 4 is devoted to interior estimates on regular elements for difference quotients. It is shown here how arbitrary derivatives of u can be approximated to optimal order $O(h^r + k^\nu)$ by difference quotients of U^n , and also that (for T_h satisfying (iib)) the effect of the Bramble-Schatz averaging operator is not spoiled by time discretization so that $O(h^{2r-2} + k^\nu)$ approximations can also be found.

After giving examples, in Section 5, of specific rational functions satisfying our assumptions, we conclude the paper by deriving in Section 6, L_2 error estimates for schemes using successively a finite number of different choices of rational functions, time steps and approximating function spaces, and also for schemes using initial data other than $P_0 v$.

We now turn to the classification of the discretization in time. First, the rational approximations to $e^{-\tau}$ are said to be of types I, II, III or IV, respectively, if

- I: $|\mathcal{r}(\tau)| < 1$ for $0 < \tau < \alpha$, for some $\alpha > 0$;
- II: $|\mathcal{r}(\tau)| < 1$ for $\tau > 0$;
- III: $\sup_{\tau > \delta} |\mathcal{r}(\tau)| < 1$ for all $\delta > 0$;
- IV: $|\mathcal{r}(\tau)| < 1$ for $\tau > 0$ and $\lim_{\tau \rightarrow \infty} \mathcal{r}(\tau) = 0$.

Notice that these conditions are successively more restrictive.

The discretization scheme (1.7) is now classified by these conditions on $\mathcal{r}(\tau)$, assuming always the conditions (i), (iia) placed previously on T_h (when (iib) is needed this will be explicitly stated). In certain cases, we shall need to impose, in addition, restrictions on the relation between the parameters h and k occurring in (1.7). More precisely, we shall say that the scheme is of type I', II' or III' if, with Λ_{\max} the maximal eigenvalue of L_h ,

- I': $\mathcal{r}(\tau)$ is of type I and $k\Lambda_{\max} \leq \alpha_0$ for some α_0 , $0 < \alpha_0 < \alpha$;
- II': $\mathcal{r}(\tau)$ is of type II and $k\Lambda_{\max} \leq \alpha_1$ for some α_1 , $0 < \alpha_1 < \infty$;
- III': $\mathcal{r}(\tau)$ is of type III and $k^s \Lambda_{\max} \leq \alpha_s$ for some α_s , $0 < \alpha_s < \infty$, and $s \geq 1$.

A scheme of type III or IV will simply be one for which $\mathcal{r}(\tau)$ is of type III or IV, respectively, with no restriction on the relation between k and Λ_{\max} .

Notice that for schemes of types I' and II', setting $\tau_0 = \alpha_0$ and α_1 , respectively, we have $0 < k\lambda \leq \tau_0$ for λ in σ_h , the spectrum of L_h , and hence $|\mathcal{r}(k\lambda)| < 1$ for $\lambda \in \sigma_h$ so that, in fact,

$$|\tau(k\lambda)| \leq e^{-ck\lambda} \quad \text{for } \lambda \in \sigma_h, \text{ with } c > 0.$$

This fact will be used repeatedly in the proofs.

In order that the condition $k\Lambda_{\max} \leq \tau_0$ be satisfied it is sufficient that

$$(1.14) \quad \Lambda_{\max} \leq \kappa_0 h^{-2},$$

and that the mesh ratio condition $k/h^2 \leq \tau_0/\kappa_0$ hold. For schemes of type I' this is analogous to the mesh ratio restrictions necessary for explicit difference schemes whereas for schemes of type II' this mesh ratio is only required to be bounded above. For the standard Galerkin method, for example, (1.14) would follow from an inverse assumption

$$\|\chi\|_1 \leq Ch^{-1} \|\chi\|_0, \quad \forall \chi \in S_h.$$

The condition for schemes of type III' would be satisfied if $\Lambda_{\max} \leq \kappa_0 h^{-\sigma_0}$ holds and k/h^{σ_1} is bounded, with σ_0 and σ_1 arbitrary positive ($s = \sigma_0/\sigma_1$).

Of the results quoted above for nonsmooth data, the L_2 estimate (1.12) is proved for schemes of types I', II' and III, the maximum-norm estimates for schemes of types I', II', III' and IV, and the interior estimates for difference quotients for types I', II' and IV. The estimate (1.13) for smooth data holds for schemes of types I' and II.

Particular fully discrete Galerkin methods for parabolic problems have been treated in the literature by various authors. For instance, using energy methods and assuming a smooth solution, Douglas and Dupont [6], Dupont [7] and Wheeler [14] considered the Crank-Nicolson scheme, Zlámal [15] the so-called Calahan scheme (see below) and Crouzeix [5] schemes based on implicit Runge-Kutta methods for ordinary differential equations. Further, a theory for schemes employing general rational functions, allowing also subspaces with elements not necessarily satisfying the boundary conditions, was developed in Bramble and Thomée [4]. Except for the case of rational functions with numerators and denominators at most linear, these schemes are different from the ones studied here. The case of nonsmooth data was considered in Blair [1] for the simplest backward difference method in time and in Thomée [12], where classifications of the above types and techniques similar to the ones of the present paper were employed in one space dimension. The third author wishes to point out that the proof of the main result concerning completely discrete schemes with nonsmooth data in [12] (Theorem 4.2) is incorrect, in that the analysis relies on an eigenfunction expansion of the form (1.10) and hence pertains to the appropriate special case of the presently studied scheme (1.7), rather than to the scheme proposed in [4].

Let us emphasize again that our formulation and analysis here only requires the availability of an approximate solution operator T_h for the elliptic problem, with the above properties, and that no further smoothness and other requirements are necessary for the subspaces S_h . This is in contrast to the investigations in Bramble and Thomée [4] where higher accuracy in the time discretization necessitated higher smoothness of the approximating functions.

Specific examples of rational functions of types I, II and IV are provided by the

above diagonal, diagonal and below diagonal entries of the Padé table for $e^{-\tau}$. Other examples of completely discrete schemes and their computational implementation are described in Section 5 below. In particular we consider some classes of schemes of types III and IV where the rational functions are defined by taking appropriate truncations of a series expansion of the form

$$e^{-\tau} = 1 - \sum_{j=0}^{\infty} P_j(b) \left(\frac{\tau}{1 + b\tau} \right)^{j+1} \quad \text{with } b > 0,$$

where the coefficients P_j are real polynomials associated with the Laguerre polynomials of the first order. For given ν , the rational function thus derived will have denominator $(1 + b\tau)^{\nu-1}$. This, as follows from the discussion following the introduction of the scheme (1.7), means that computationally, $\nu - 1$ systems, all with the same matrix will have to be solved at each time step. Such a property should be desirable from a practical point of view. These rational functions were studied and used for stiff systems of ordinary differential equations by Nørsett [11]; the particular case $\nu = 3$ was applied by Zlámal [15] to parabolic problems and referred to as the Calahan scheme (cf. also Makinson [9]).

Throughout this paper, C and c will denote positive constants, not necessarily the same at different occurrences.

2. Error Estimates in L_2 . Our first result in this section is an L_2 estimate for the difference between the semidiscrete and completely discrete solutions, with initial data only assumed to belong to $L_2(\Omega)$. Together with the estimates from [3] for the error in the semidiscrete solution, this results in a complete error estimate for U^n . This estimate has optimal order of accuracy for t bounded away from zero, but contains a negative power of t on the right.

We now state this first result.

THEOREM 2.1. *Let the discretization scheme be of type I', II' or III. Then for $0 < t = nk \leq t^*$,*

$$\|U^n - u_h(nk)\| \leq Ck^\nu t^{-\nu} \|v\|.$$

Before giving the proof of this result we shall introduce some notation. For an arbitrary function $g(\tau)$ defined for $\tau \in \sigma_h$, the spectrum of $L_h = T_h^{-1}$, we set for $v \in L_2(\Omega)$,

$$(2.1) \quad g(L_h)v = \sum_{\Lambda_j \in \sigma_h} g(\Lambda_j)(v, \Phi_j)\Phi_j = g(L_h)P_0v.$$

In particular, with

$$(2.2) \quad F_n(\tau) = r(\tau)^n - e^{-n\tau},$$

we can write

$$(2.3) \quad U^n - u_h(nk) = F_n(kL_h)v.$$

By (2.1), L_h is defined on all of L_2 and not just as the inverse of T_h on S_h . By Parseval's relation we have for the operator norm of $g(L_h)$ on L_2 ,

$$(2.4) \quad \|g(L_h)\| = \sup_{\tau \in \sigma_h} |g(\tau)|.$$

In view of (2.3), Theorem 2.1 is a consequence of the following lemma:

LEMMA 2.1. *Let the discretization scheme be of type I', II' or III. Then for $0 < t = nk \leq t^*$,*

$$\|F_n(kL_h)\| \leq Ck^\nu t^{-\nu}.$$

Proof. We have by (2.4),

$$\|F_n(kL_h)\| = \sup_{\lambda \in \sigma_h} |F_n(k\lambda)| = \sup_{\tau/k \in \sigma_h} |F_n(\tau)|,$$

and hence it suffices to show that

$$|F_n(\tau)| \leq C(k/t)^\nu = Cn^{-\nu} \quad \text{for } \tau/k \in \sigma_h.$$

Let τ_0 be a positive number such that

$$(2.5) \quad |r(\tau)| < 1 \quad \text{for } 0 < \tau \leq \tau_0.$$

Then for $0 < \tau \leq \tau_0$ by (1.8),

$$|r(\tau) - e^{-\tau}| \leq C\tau^{\nu+1},$$

and

$$(2.6) \quad |r(\tau)| \leq e^{-c\tau} \quad \text{with } 0 < c < 1.$$

Hence

$$(2.7) \quad |F_n(\tau)| = \left| (r(\tau) - e^{-\tau}) \sum_{l=0}^{n-1} r(\tau)^{n-1-l} e^{-l\tau} \right| \\ \leq Cn\tau^{\nu+1} e^{-c(n-1)\tau} \leq C\tau^\nu e^{-cn\tau} \leq Cn^{-\nu}.$$

Since in cases I' and II', $k\lambda \leq \tau_0$ for all $\lambda \in \sigma_h$ if τ_0 is appropriately chosen, this completes the proof for such schemes. For type III schemes we also have to consider τ large, $\tau \geq 1$, say. We then have

$$e^{-n\tau} \leq e^{-n} \leq Cn^{-\nu}.$$

Further,

$$(2.8) \quad \sup_{\tau \geq 1} |r(\tau)| = e^{-c} \quad \text{with } c > 0,$$

so that similarly

$$|r(\tau)^n| \leq e^{-cn} \leq Cn^{-\nu} \quad \text{for } \tau \geq 1.$$

This completes the proof.

Combining Theorem 2.1 with the case $j = 0$ of Theorem 3.2 in [3], which states that

$$(2.9) \quad \|u_h(t) - u(t)\| \leq Ch^\nu t^{-\nu/2} \|v\| \quad \text{for } 0 < t \leq t^*,$$

we conclude immediately:

THEOREM 2.2. *Let the discretization scheme be of type I', II' or III. Then for $0 < t = nk \leq t^*$,*

$$\|U^n - u(nk)\| \leq C\{h^r t^{-r/2} + k^\nu t^{-\nu}\} \|v\|.$$

We shall now turn to estimates which hold uniformly down to $t = 0$. In this case, in order to obtain optimal order results, smoothness has to be required of the initial data. In Theorem 2.1 of [3], before proving the estimate (2.9), the energy method was used to derive such an error estimate for the semidiscrete solution; in particular

$$(2.10) \quad \|u_h(t) - u(t)\| \leq Ch^s \|u\|_s \quad \text{for } 0 \leq s \leq r, 0 \leq t \leq t^*.$$

In order to obtain now a similar result for the completely discrete situation we shall combine Theorem 2.1 with the following representation of the initial data, namely

$$(2.11) \quad v = \sum_{j=0}^{\nu-1} T_h^j (T - T_h) L^{j+1} v + T_h^\nu L^\nu v.$$

The following lemma will be needed.

LEMMA 2.2. *Let the discretization scheme be of type I' or II. Then for $0 \leq j \leq \nu$,*

$$\|T_h^j F_n(kL_h)\| \leq Ck^j.$$

Proof. By (2.4),

$$\|T_h^j F_n(kL_h)\| = \sup_{\lambda \in \sigma_h} |\lambda^{-j} F_n(k\lambda)| = \sup_{\tau/k \in \sigma_h} |k^j \tau^{-j} F_n(\tau)|,$$

and hence it suffices to show that

$$|\tau^{-j} F_n(\tau)| \leq C \quad \text{for } \tau/k \in \sigma_h.$$

As in the proof of Lemma 2.1, let τ_0 be a positive number such that $|r(\tau)| < 1$ for $0 < \tau \leq \tau_0$. Then for such τ , by (1.8)

$$|r(\tau) - e^{-\tau}| \leq C\tau^{j+1}, \quad 0 \leq j \leq \nu,$$

and (2.6) holds.

Hence

$$|\tau^{-j} F_n(\tau)| = \left| \tau^{-j} (r(\tau) - e^{-\tau}) \sum_{l=0}^{n-1} r(\tau)^{n-1-l} e^{-l\tau} \right| \leq Cn\tau e^{-c(n-1)\tau} \leq C.$$

For $\tau > \tau_0$ the desired inequality follows trivially.

The result in the smooth data case is then the following:

THEOREM 2.3. *Let the discretization scheme be of type I' or II. Then for $0 \leq t = nk \leq t^*$,*

$$\|U^n - u(nk)\| \leq C(h^r \|v\|_r + k^\nu \|v\|_{2\nu}).$$

Proof. We first note that if we set

$$v_k = \sum_{k\lambda_j \leq 1} (v, \varphi_j)\varphi_j$$

(recalling that φ_j and λ_j are the eigenfunctions and eigenvalues of the differential operator L) then by the definition of the norms in H^s ,

$$(2.12) \quad \|v - v_k\| \leq k^\nu \|v\|_{2\nu},$$

$$(2.13) \quad \|v_k\|_{2\nu} \leq \|v\|_{2\nu},$$

$$(2.14) \quad \|v_k\|_{r+2j} \leq k^{-j} \|v\|_r, \quad j = 0, 1, \dots$$

Applying the identity (2.11) to v_k and setting for brevity $F_n = F_n(kL_h)$ as defined by (2.1) and (2.2), we may write

$$F_n v_k = \sum_{j=0}^{\nu-1} F_n T_h^j (T - T_h) L^{j+1} v_k + F_n T_h^\nu L^\nu v_k.$$

Here, by Lemma 2.2 and (2.13),

$$\begin{aligned} \|F_n T_h^\nu L^\nu v_k\| &= \|T_h^\nu F_n L^\nu v_k\| \\ &\leq Ck^\nu \|L^\nu v_k\| = Ck^\nu \|v_k\|_{2\nu} \leq Ck^\nu \|v\|_{2\nu}. \end{aligned}$$

Further, using also (iia) and (2.14), we obtain for $0 \leq j \leq \nu - 1$,

$$\begin{aligned} \|F_n T_h^j (T - T_h) L^{j+1} v_k\| &\leq Ck^j \|(T - T_h) L^{j+1} v_k\| \\ &\leq Ck^j h^r \|L^{j+1} v_k\|_{r-2} = Ck^j h^r \|v_k\|_{r+2j} \\ &\leq Ch^r \|v\|_r \leq Ch^r \|v\|_r. \end{aligned}$$

Together, these estimates imply

$$\|F_n v_k\| \leq C(h^r \|v\|_r + k^\nu \|v\|_{2\nu}).$$

Since obviously, by stability (cf. (1.11)) and (2.12),

$$\|F_n(v - v_k)\| \leq 2\|v - v_k\| \leq Ck^\nu \|v\|_{2\nu},$$

we conclude that

$$\|U^n - u_h(nk)\| = \|F_n v\| \leq C(h^r \|v\|_r + k^\nu \|v\|_{2\nu}).$$

By (2.10) (with $s = r$) this completes the proof.

It is also possible to prove estimates which are uniform in t for less regular initial data. We have for instance:

THEOREM 2.4. *Let the discretization scheme be of type I' or II and let $s \geq 0$. Then for $0 \leq t = nk \leq t^*$,*

$$\|U^n - u(nk)\| \leq C\{h^{\min(r,s)} + k^{\min(\nu,s/2)}\} \|v\|_s.$$

Proof. We first notice that in Theorem 2.3 and its proof we may replace r by any s_1 with $2 \leq s_1 \leq r$. Using also the fact that the function v_k satisfies, for $0 \leq s_2 \leq 2\nu$,

$$\|v - v_k\| \leq k^{s_2/2} \|v\|_{s_2}, \quad \|v_k\|_{2\nu} \leq k^{-(\nu-s_2/2)} \|v\|_{s_2},$$

we obtain

$$\|U^n - u(nk)\| \leq C\{h^{s_1}\|v\|_{s_1} + k^{s_2/2}\|v\|_{s_2}\}.$$

In particular, this proves the desired result for $s \geq 2$. Interpolation between the result for $s = 2$ and the stability estimate

$$\|U^n - u(nk)\| \leq 2\|v\|,$$

now completes the proof.

We shall conclude this section by considering a finite difference approximation for a time derivative $D_t^l u$ of the solution of the parabolic problem, of the form

$$q_k U^n = k^{-l} q(E) U^n,$$

where

$$q(E) = \sum_{j=j_0}^{j_1} q_j E^j, \quad E^j U^n = U^{n+j}.$$

Notice that this approximation will be defined only for $n + j_0 \geq 0$. Recall that the operator q_k is an approximation of order ν to D_t^l if

$$(2.15) \quad q(e^{-\tau}) = \sum_{j=j_0}^{j_1} q_j e^{-j\tau} = (-\tau)^l + O(\tau^{l+\nu}) \quad \text{as } \tau \rightarrow 0.$$

Notice that then, by (1.7),

$$(2.16) \quad q(r(\tau)) = (-\tau)^l + O(\tau^{l+\nu}) \quad \text{as } \tau \rightarrow 0.$$

We then have the following optimal order error estimate for t bounded away from zero and initial data in L_2 .

THEOREM 2.5. *Assume that q_k is an approximation of order ν to D_t^l and that the scheme is of type I', II' or III. Then for $0 < t = nk \leq t^*$, with $n + j_0 \geq 0$,*

$$\|q_k U^n - D_t^l u(nk)\| \leq C(h^r t^{-r/2-l} + k^\nu t^{-\nu-l})\|v\|.$$

Proof. By Theorem 3.2 of [3] we have

$$\|D_t^l(u_h(t) - u(t))\| \leq Ch^r t^{-r/2-l}\|v\|,$$

and so it remains to prove

$$\|q_k U^n - D_t^l u_h(nk)\| \leq Ck^\nu t^{-\nu-l}\|v\|.$$

By the spectral representation we have

$$q_k U^n - D_t^l u_h(nk) = \sum_j (k^{-l} q(r(k\Lambda_j))r(k\Lambda_j)^n - (-\Lambda_j)^l e^{-\tau\Lambda_j})(v, \Phi_j)\Phi_j,$$

so that setting

$$s_n(\tau) = q(r(\tau))r(\tau)^n - (-\tau)^l e^{-n\tau},$$

our result would follow from

$$\sup_{\lambda \in \sigma_h} |k^{-l} s_n(k\lambda)| \leq Ck^\nu t^{-\nu-l}$$

or

$$(2.17) \quad |s_n(\tau)| \leq Cn^{-\nu-l} \quad \text{for } \tau/k \in \sigma_h.$$

Now let τ_0 be as in the proof of Lemma 2.1 (cf. (2.5)) and write

$$s_n(\tau) = (q(r(\tau)) - (-\tau)^l)r(\tau)^n + (-\tau)^l(r(\tau)^n - e^{-n\tau}).$$

Using (2.16) and (2.6) we obtain for $\tau \leq \tau_0$,

$$(2.18) \quad |(q(r(\tau)) - (-\tau)^l)r(\tau)^n| \leq C\tau^{l+\nu}e^{-cn\tau} \leq Cn^{-l-\nu},$$

and by (2.7),

$$(2.19) \quad |\tau^l(r(\tau)^n - e^{-n\tau})| \leq C\tau^{\nu+l}e^{-cn\tau} \leq Cn^{-l-\nu};$$

so that

$$|s_n(\tau)| \leq Cn^{-l-\nu} \quad \text{for } \tau \leq \tau_0.$$

This completes the proof of (2.17) for schemes of types I' and II'. In the case of type III we also consider $\tau \geq 1$, say. For such τ ,

$$\tau^l e^{-n\tau} \leq \tau^{l+\nu} e^{-n\tau} \leq Cn^{-l-\nu},$$

and

$$|q(r(\tau))r(\tau)^n| \leq Ce^{-cn} \leq Cn^{-l-\nu}.$$

This completes the proof of (2.17) for $\tau \geq 1$ and hence of the theorem.

3. Error Estimates in the Maximum Norm. In this section we shall derive maximum norm estimates, analogous to those of Section 4 of [3] for the semidiscrete problem, for our completely discrete approximations. In [3] it was shown that if certain maximum norm error estimates were available for the associated elliptic problem, then corresponding maximum norm error estimates could be derived for t bounded away from zero for the parabolic problem.

The assumption about the elliptic problem, which will also be made here, was that there is a function $\gamma(h)$ such that

$$(i)' \quad |T_h w| \leq C|Tw|_1, \quad \|T_h w\| \leq C\|Tw\|_1,$$

$$(ii)' \quad |(T_h - T)w| \leq \gamma(h)|Tw|_r,$$

where $|\cdot|$ and $|\cdot|_r$ denote the norms in $C(\bar{\Omega})$ and $C^r(\bar{\Omega})$, respectively. The conclusion for our semidiscrete problem was [3, Theorem 4.2] that

$$(3.1) \quad |u_h(t) - u(t)| \leq C\{\gamma(h) + h^r\}\|v\| \quad \text{for } 0 < t_* \leq t \leq t^*.$$

In special cases discussed in Section 8 of [3], $\gamma(h) = Ch^r$ for $r > 2$ and $\gamma(h) = Ch^2 \log h^{-1}$ for $r = 2$.

To obtain our error estimate for the completely discrete problem we shall again use the spectral representation

$$(3.2) \quad U^n - u_h(nk) = F_n(kL_h)v = \sum_j F_n(k\Lambda_j)(v, \Phi_j)\Phi_j.$$

The technique will now be to derive first a maximum norm estimate for φ_j , and then an estimate for $F_n(k\Lambda_j)$.

We first have:

LEMMA 3.1. *Under the above assumptions (i)', (ii)' on T_h there exists a J depending only on N such that*

$$|\Phi_j| \leq C\Lambda_j^J.$$

Proof. By Lemma 4.1 of [3] we have for $2 \leq p \leq \infty$, $0 < 1/q - 1/p < 1/N$,

$$\|T_h w\|_{L_p} \leq C\|w\|_{L_q}.$$

In particular, then

$$\|\Phi_j\|_{L_p} = \Lambda_j \|T_h \Phi_j\|_{L_p} \leq C\Lambda_j \|\Phi_j\|_{L_q}.$$

Hence, by repeated application, using a suitable decreasing sequence $\{p_j\}_0^J$ with $p_0 = \infty$, $p_J = 2$, $1/p_{j+1} - 1/p_j < 1/N$ we obtain

$$|\Phi_j| \leq C\Lambda_j^J \|\Phi_j\| = C\Lambda_j^J,$$

which proves the lemma.

The next lemma, which we shall also use in the next section, contains the needed estimate for $F_n(k\Lambda_j)$.

LEMMA 3.2. *Let the scheme be of type I', II', III' or IV. Then for $0 < t = nk \leq t^*$ and $j \geq 0$,*

$$\|L_h^j F_n(kL_h)\| = \sup_{\lambda \in \sigma_h} |\lambda^j F_n(k\lambda)| \leq Ck^\nu t^{-\nu-\rho_j}$$

where $\rho = 1$ for types I', II' and IV and $\rho = s$ for type III' (with parameter s).

Proof. Let τ_0 be as in (2.5) and consider first $\tau = k\lambda \leq \tau_0$. We want to show that then

$$(3.3) \quad |\lambda^j F_n(k\lambda)| = |k^{-j} \tau^j F_n(\tau)| \leq Ck^\nu t^{-j-\nu}.$$

But, applying (2.7) with $j = 0$, we obtain at once

$$|\tau^j F_n(\tau)| \leq C\tau^{j+\nu} e^{-cn\tau} \leq Cn^{-j-\nu} = Ck^{j+\nu} t^{-j-\nu},$$

which proves (3.3). This completes the proof for schemes of types I' and II'.

For schemes of types III' and IV we also have, as usual, to consider $\tau = k\lambda \geq 1$, for $\lambda \in \sigma_h$. In both cases we have, by obvious estimates,

$$\lambda^j e^{-n\tau} = k^{-j} \tau^j e^{-n\tau} \leq Ck^{-j} n^{-j} e^{-cn\tau} \leq Ct^{-j} n^{-\nu} = Ck^\nu t^{-j-\nu}.$$

Now, in case III' we have by definition and (2.8), for $\lambda \in \sigma_h$,

$$|\lambda^j r(\tau)^n| \leq Ck^{-sj}e^{-cn} \leq Ck^{-sj}n^{-\nu-sj} = Ck^\nu t^{-\nu-sj}.$$

Since $s \geq 1$, the above estimates complete the proof for case III'.

Finally, for type IV, the degree of the numerator of $r(\tau)$ is less than that of the denominator and it follows that there is a $c > 0$ such that

$$|r(\tau)| \leq \frac{1}{1 + c\tau} \quad \text{for } \tau \geq 1.$$

Hence for these τ ,

$$\begin{aligned} (3.4) \quad |k^{-j}\tau^j r(\tau)^n| &\leq k^{-j}(\tau/(1 + c\tau))^j(1 + c\tau)^{-(n-j)} \\ &\leq Ck^{-j}(1 + c)^{-n} \leq Ck^{-j}n^{-\nu-j} = Ck^\nu t^{-\nu-j}. \end{aligned}$$

This completes the proof in case IV and hence the lemma is proved.

In order to state and prove our main result of this section we shall make the additional assumption that the eigenvalues Λ_j of L_h tend to infinity fast enough that for some J_0 , uniformly for small h ,

$$(iii) \quad \sum_j \Lambda_j^{-J_0} \leq C < \infty.$$

For instance, if we consider the standard Galerkin method, with the elements of S_h vanishing on $\partial\Omega$ (cf. Section 8.1 of [3]), it is well known that $\Lambda_j \geq \lambda_j$, and (iii) then follows from known estimates for the spectrum of the elliptic operator L .

THEOREM 3.1. *Assume that (i)', (ii)' and (iii) hold and let the discretization scheme be of type I', II', III' or IV. Then for $0 < t_* \leq t = nk \leq t^*$,*

$$|U^n - u(nk)| \leq C(\gamma(h) + h^r + k^\nu)\|v\|.$$

Proof. By (3.1) it suffices to show that for $t = nk$ bounded away from zero and infinity,

$$(3.5) \quad |U^n - u_h(nk)| \leq Ck^\nu\|v\|.$$

But by (3.2) and Lemma 3.1,

$$(3.6) \quad |U^n - u_h(nk)| \leq \left(\sum_j |F_n(k\Lambda_j)| |\Phi_j| \right) \|v\| \leq C \left(\sum_j \Lambda_j^J |F_n(k\Lambda_j)| \right) \|v\|.$$

In view of (iii) it therefore suffices to notice that by Lemma 3.2,

$$|F_n(k\Lambda_j)| \leq Ck^\nu t^{-\nu-\rho(J+J_0)} \Lambda_j^{-(J+J_0)}.$$

This completes the proof of the lemma.

Notice that we actually have the somewhat stronger statement than (3.5), namely

$$|U^n - u_h(nk)| \leq Ck^\nu\|v\|_{L_1(\Omega)}.$$

For, instead of (3.6) we can similarly derive

$$\begin{aligned} |U^n - u_h(nk)| &\leq \left(\sum_j |F_n(k\Lambda_j)| |\Phi_j|^2 \right) \|v\|_{L_1(\Omega)} \\ &\leq C \left(\sum_j \Lambda_j^{2J} |F_n(k\Lambda_j)| \right) \|v\|_{L_1(\Omega)} \leq Ck^\nu t^{-\nu-\rho(J_0+2J)} \|v\|_{L_1(\Omega)}. \end{aligned}$$

4. Interior Estimates for Difference Quotients. In this section we shall derive L_2 error estimates for difference quotients of $U^n - u_h(nk)$ on some interior subdomain Ω_0 of Ω , under certain additional assumptions on S_h and T_h . We shall then apply these estimates to extend to the completely discrete case the study of Sections 6 and 7 of [3] concerning approximation in the maximum norm of derivatives of the solution of the continuous problem, including approximations of superconvergent order $O(h^{2r-2})$.

Here, in addition to the norms in $\dot{H}^s(\Omega)$ we shall use for $s \geq 0$ the norm $\|\cdot\|_{s, \Omega_0}$ on $H^s(\Omega_0) = W_2^s(\Omega_0)$ (denoted $\|\cdot\|_{\Omega_0}$ when $s = 0$) and the norm of negative order $-s$,

$$\|w\|_{-s, \Omega_0} = \sup_{\varphi \in C_0^\infty(\Omega_0)} \frac{(w, \varphi)}{\|\varphi\|_{s, \Omega_0}}.$$

Further, $|\cdot|_{\Omega_0}$ and $|\cdot|_{s, \Omega_0}$ will be used to denote the norms in $C(\bar{\Omega}_0)$ and $C^s(\bar{\Omega}_0)$, respectively.

The first of our additional assumptions is that T_h satisfies the ‘‘interior’’ equation

$$(4.1) \quad A(T_h f, \chi) = (f, \chi), \quad \forall \chi \in S_h^0(\Omega_0),$$

where $S_h^0(\Omega_0)$ is the set of functions in S_h with supports in Ω_0 and $A(\cdot, \cdot)$ is the bilinear form (1.6). This implies that the solution u_h of the semidiscrete problem satisfies the interior parabolic Galerkin equation

$$(D_t u_h, \chi) + A(u_h, \chi) = 0, \quad \forall \chi \in S_h^0(\Omega_0), \quad t > 0.$$

We shall further require that on Ω_0 the functions in S_h be piecewise polynomials on a uniform partition. The precise conditions needed, which will be referred to as r -regularity of $\{S_h\}$ on Ω_0 , are stated in Section 6 of [3], and rather than restating them here, we shall quote only the consequences needed for our present purposes.

In particular, setting

$$\partial_h^\alpha = \partial_{h,1}^{\alpha_1} \cdots \partial_{h,N}^{\alpha_N} \quad \text{with } \partial_{h,j} w(x) = h^{-1}(w(x + he_j) - w(x)),$$

where e_j is the unit vector in the direction of x_j , it follows under these assumptions from Lemma 6.4 and Theorem 3.2 of [3] that for $\Omega_1 \subset\subset \Omega_0$ and for $0 < t_* \leq t \leq t^*$,

$$(4.2) \quad \|\partial_h^\alpha D_t^j(u_h(t) - u(t))\|_{\Omega_1} \leq Ch^r \|v\|.$$

Using also a discrete Sobolev inequality this could be seen to imply (cf. [3, Lemma 6.5]) that for $\Omega_1 \subset\subset \Omega_0$ and $0 < t_* \leq t \leq t^*$,

$$(4.3) \quad |\partial_h^\alpha D_t^j(u_h(t) - u(t))|_{\Omega_1} \leq Ch^r \|v\|.$$

Similarly, using Lemma 7.3 and Theorems 3.1 and 3.2 of [3] we find for $\Omega_1 \subset\subset \Omega_0$, $0 < t_* \leq t \leq t^*$,

$$(4.4) \quad \|\partial_h^\alpha D_t^j(u_h(t) - u(t))\|_{-(r-2), \Omega_1} \leq Ch^{2r-2} \|v\|_{r-2}.$$

Such estimates were the basis for deriving the maximum norm and superconvergent order error estimates in [3] referred to above. These estimates will be stated more precisely below.

In the technical work we shall need the following special case of Theorem 5.2, (5.6) in Nitsche and Schatz [10].

LEMMA 4.1. *Let $\{S_h\}$ be r -regular on $\Omega_0 \subset \Omega$ and let $\Omega_2 \subset\subset \Omega_1 \subset\subset \Omega_0$. Assume that $v_h \in S_h$ satisfies*

$$A(v_h, \chi) = f_h(\chi), \quad \forall \chi \in S_h^0(\Omega_0),$$

where f_h is a linear functional on $H_0^1(\Omega_1)$. Then

$$\|v_h\|_{1, \Omega_2} \leq C\{\|f_h\|_{-1, \Omega_1} + \|v_h\|_{\Omega_1}\},$$

where

$$\|f_h\|_{-1, \Omega_1} = \sup_{\varphi \in C_0^\infty(\Omega_1)} \frac{|f_h(\varphi)|}{\|\varphi\|_1}.$$

The subsequent proofs of the present analogues of (4.2) and (4.3) depend on the following lemma.

LEMMA 4.2. *Assume that $\{S_h\}$ is r -regular in $\Omega_0 \subset \Omega$ and that T_h satisfies the interior equation (4.1). Then for $|\alpha| \leq 2m$, $\Omega_1 \subset\subset \Omega_0$,*

$$(4.5) \quad \|\partial_h^\alpha \chi\|_{\Omega_1} \leq C\|L_h^m \chi\|, \quad \forall \chi \in S_h.$$

Proof. As a first step we shall show that if $\Omega_2 \subset\subset \Omega_1 \subset\subset \Omega_0$ and $n \geq 0$, then for $|\alpha| \leq n + 1$,

$$(4.6) \quad \|\partial_h^\alpha T_h f\|_{1, \Omega_2} \leq C \left\{ \sum_{|\beta| \leq n} \|\partial_h^\beta f\|_{\Omega_1} + \|T_h f\|_{\Omega_1} \right\}.$$

Set $v_h = T_h f$ and let $\Omega'_0 \subset\subset \Omega_0$. We have for $\chi \in S_h^0(\Omega'_0)$ and small h ,

$$\begin{aligned} A(\partial_h^\alpha v_h, \chi) &= \int_{\Omega} \left(\sum_{j,k} a_{jk} \frac{\partial}{\partial x_j} (\partial_h^\alpha v_h) \frac{\partial}{\partial x_k} \chi + c \partial_h^\alpha v_h \chi \right) dx \\ (4.7) \quad &= \int_{\Omega} \left(\sum_{j,k} \partial_h^\alpha \left(a_{jk} \frac{\partial}{\partial x_j} v_h \right) \frac{\partial}{\partial x_k} \chi + \partial_h^\alpha (c v_h) \cdot \chi \right) dx + \tilde{f}_h(\chi) \\ &= (-1)^{|\alpha|} A(v_h, \partial_h^\alpha \chi) + \tilde{f}_h(\chi), \end{aligned}$$

where for $\varphi \in C_0^\infty(\Omega'_1)$, with $\Omega'_1 \subset\subset \Omega_1$ (cf. [10, (6.7)]),

$$(4.8) \quad |\tilde{f}_h(\varphi)| \leq C \sum_{|\beta| < |\alpha|} \|\partial_h^\beta v_h\|_{1, \Omega_1} \cdot \|\varphi\|_{1, \Omega'_1}.$$

(For the case of constant coefficients, $\tilde{f}_h = 0$.) Since $\partial_h^\alpha \chi \in S_h^0(\Omega_0)$ for $\chi \in S_h^0(\Omega'_0)$ and small h , we have

$$(4.9) \quad A(v_h, \partial_h^\alpha \chi) = (f, \partial_h^\alpha \chi),$$

and since $|\alpha| \leq n + 1$, for $\varphi \in C_0^\infty(\Omega'_1)$,

$$(4.10) \quad |(f, \partial_h^\alpha \varphi)| \leq C \sum_{|\beta| \leq n} \|\partial_h^\beta f\|_{\Omega_1} \|\varphi\|_{1, \Omega_1'}.$$

Together, (4.7), (4.8), (4.9) and (4.10) show by Lemma 4.1,

$$\|\partial_h^\alpha v_h\|_{1, \Omega_2} \leq C \left\{ \sum_{|\beta| \leq n} \|\partial_h^\beta f\|_{\Omega_1} + \sum_{|\beta| < |\alpha|} \|\partial_h^\beta v_h\|_{1, \Omega_1} \right\}.$$

Hence by repeated application, for any $\Omega_2 \subset\subset \Omega_1 \subset\subset \Omega_0$,

$$\|\partial_h^\alpha v_h\|_{1, \Omega_2} \leq C \left\{ \sum_{|\beta| \leq n} \|\partial_h^\beta f\|_{\Omega_1} + \|v_h\|_{1, \Omega_1} \right\}.$$

Using Lemma 4.1 once more to estimate the last term we conclude for $\Omega_2 \subset\subset \Omega_1$,

$$\|\partial_h^\alpha v_h\|_{1, \Omega_2} \leq C \left\{ \sum_{|\beta| \leq n} \|\partial_h^\beta f\|_{\Omega_1} + \|v_h\|_{\Omega_1} \right\},$$

which is (4.6).

As a consequence of (4.6), we have also, now for $|\alpha| \leq n + 2$, again with $\Omega_2 \subset\subset \Omega_1 \subset\subset \Omega_0$,

$$(4.11) \quad \|\partial_h^\alpha T_h f\|_{\Omega_2} \leq C \left\{ \sum_{|\beta| \leq n} \|\partial_h^\beta f\|_{\Omega_1} + \|T_h f\|_{\Omega_1} \right\}.$$

We are now in a position to prove (4.5) by induction over m . The statement being obvious for $m = 0$ we consider the step from m to $m + 1$. For $|\alpha| \leq 2m + 2$ we then obtain by (4.11) for $\chi \in S_h$,

$$\|\partial_h^\alpha \chi\|_{\Omega_1} = \|\partial_h^\alpha T_h L_h \chi\|_{\Omega_1} \leq C \left\{ \sum_{|\beta| \leq 2m} \|\partial_h^\beta L_h \chi\|_{\Omega_2} + \|\chi\|_{\Omega_2} \right\},$$

and hence by the induction assumption and the boundedness of T_h ,

$$\|\partial_h^\alpha \chi\|_{\Omega_1} \leq C \{ \|L_h^m L_h \chi\| + \|\chi\| \} \leq C \|L_h^{m+1} \chi\|,$$

which completes the proof.

We can now state and prove the present analogues of (4.2) and (4.3).

THEOREM 4.1. *Assume that $\{S_h\}$ is r -regular in $\Omega_0 \subset \Omega$ and that (4.1) holds. Let $q_k = k^{-l} q(E)$ approximate D_t^l with accuracy ν in the sense of (2.15). Then for completely discrete schemes of types I', II' and IV, we have for any α , $\Omega_1 \subset\subset \Omega_0$ and $0 < t = nk \leq t^*$,*

$$(4.12) \quad \|\partial_h^\alpha (q_k U^n - D_t^l u_h(nk))\|_{\Omega_1} \leq C k^\nu t^{-\nu-l-|\alpha|/2} \|v\|,$$

and with $N_0 = [N/2] + 1$,

$$(4.13) \quad |\partial_h^\alpha (q_k U^n - D_t^l u(nk))|_{\Omega_1} \leq C k^\nu t^{-\nu-l-(|\alpha|+N_0)/2} \|v\|.$$

Proof. We first show (4.12) for α of even order, $|\alpha| = 2m$. We obtain by Lemma 4.2 and (2.4),

$$\begin{aligned} \|\partial_h^\alpha(q_k U^n - D_t^l u_h(nk))\|_{\Omega_1} &\leq C \|L_h^m(q_k U^n - D_t^l u_h(nk))\| \\ &= \sup_{\lambda \in \sigma_h} |\lambda^m (k^{-l} q(r(k\lambda))r(k\lambda)^n - (-\lambda)^l e^{-nk\lambda})| \|v\| \\ &= C k^{-l-m} \sup_{\tau/k \in \sigma_h} |\tau^m s_n(\tau)| \|v\|, \end{aligned}$$

where as in the proof of Theorem 2.5,

$$s_n(\tau) = q(r(\tau))r(\tau)^n - (-\tau)^l e^{-n\tau}.$$

It therefore suffices to show that

$$(4.14) \quad |\tau^m s_n(\tau)| \leq C n^{-\nu-l-m} \quad \text{for } \tau/k \in \sigma_h.$$

Now let τ_0 be as in (2.5). Then by (2.18) and (2.19),

$$|\tau^m s_n(\tau)| \leq C \tau^{m+l+\nu} e^{-cn\tau} \leq C n^{-l-\nu-m} \quad \text{for } \tau \leq \tau_0.$$

This completes the proof of (4.14) for schemes of types I' and II'. For schemes of type IV we also need to consider $\tau \geq 1$, say. For such τ ,

$$\tau^{l+m} e^{-n\tau} \leq \tau^{l+\nu+m} e^{-n\tau} \leq C n^{-l-\nu-m},$$

and, appealing now to (3.4),

$$|\tau^{l+m} q(r(\tau))r(\tau)^n| \leq C |\tau^{l+m} r(\tau)^{n-j_0}| \leq C n^{-\nu-l-m},$$

which implies (4.14). This concludes the proof of (4.12) for $|\alpha|$ even. Notice that it is at the last step that we have to use type IV rather than type III, as was the case in Theorem 2.5.

In order to show (4.12) for $|\alpha|$ odd, we choose j such that $\alpha_j > 0$ and apply summation by parts to obtain the inequality

$$\|\partial_h^\alpha \chi\|_{\Omega_1} \leq \|\partial_h^{\alpha-e} j \chi\|_{\Omega_2}^{1/2} \|\partial_h^{\alpha+e} j \chi\|_{\Omega_2}^{1/2}, \quad \Omega_1 \subset\subset \Omega_2 \subset\subset \Omega_0.$$

With $\chi = q_k U^n - D_t^l u_h(nk)$ the result for $|\alpha|$ even hence implies the result for $|\alpha|$ odd. This concludes the proof of (4.12).

The maximum norm estimate (4.13) now follows at once by the Sobolev inequality

$$|\chi|_{\Omega_2} \leq C \sum_{|\beta| \leq N_0} \|\partial_h^\beta \chi\|_{\Omega_1} \quad \text{for } \chi \in S_h, \Omega_2 \subset\subset \Omega_1,$$

since $q_k U^n - D_t^l u_h(nk) \in S_h$. This completes the proof of the theorem.

We now turn to the maximum norm approximation of derivatives of the solution $u(t)$. We recall that the finite difference operator

$$Q_h w(x) = \sum_{\beta, \eta} q_{\beta\eta} \partial_h^\beta w(x - \eta h)$$

approximates the derivative $D^\alpha w$ of order $|\alpha| = m$ with accuracy r if for $\Omega_2 \subset\subset \Omega_1$,

$$|Q_h w - D^\alpha w|_{\Omega_2} \leq Ch^r |w|_{r+m, \Omega_1}.$$

Combining this for $w = D_t^l u(t)$ with (4.3) we concluded in [3] (cf. Theorem 6.2) that under the above assumptions on S_h and T_h , for $\Omega_1 \subset\subset \Omega_0$ and $0 < t_* \leq t \leq t^*$,

$$(4.15) \quad |Q_h D_t^l u_h(t) - D_x^\alpha D_t^l u(t)|_{\Omega_1} \leq Ch^r \|v\|.$$

The following is the corresponding result for our completely discrete approximation.

THEOREM 4.2. *Under the assumptions of Theorem 4.1, with Q_h approximating D^α with accuracy r we have for any $\Omega_1 \subset\subset \Omega_0$, $0 < t_* \leq t = nk \leq t^*$,*

$$|Q_h q_k U^n - D_x^\alpha D_t^l u(nk)|_{\Omega_1} \leq C(h^r + k^p) \|v\|.$$

Proof. We have by Theorem 4.1, with $\Omega_1 \subset\subset \Omega_2 \subset\subset \Omega_0$,

$$|Q_h q_k U^n - Q_h D_t^l u_h(nk)|_{\Omega_1} \leq C \sum_{|\beta| \leq |\alpha|} |\partial_h^\beta (q_k U^n - D_t^l u_h(nk))|_{\Omega_2} \leq Ck^p \|v\|.$$

In view of (4.15) this proves the theorem.

We now turn to the superconvergence estimates. For the semidiscrete case this was done in Section 7 of [3] for the approximation of the continuous solution itself. Here we shall generalize this to cover also derivatives. For this purpose, we will use the following lemma which is a special case of Theorem 3 in Thomée [13]. Here we denote by ψ the N -dimensional analogue of the B -spline of order $r - 2$, that is, the convolution $\chi * \dots * \chi$ with $r - 2$ factors, where χ is the characteristic function of the cube $[-\frac{1}{2}, \frac{1}{2}]^N$.

LEMMA 4.3. *Let α be a given multi-index. Then there exists a function $K_h = K_h^{(\alpha)}$ of the form*

$$K_h(x) = h^{-N} \sum_{\beta} k_{\beta} \psi(h^{-1}x - \beta),$$

with $k_{\beta} = 0$ when $|\beta_j| \geq r - 1$ such that if $\Omega_2 \subset\subset \Omega_1 \subset\subset \Omega_0$ and $w \in C^{2r-2+|\alpha|}(\Omega_0)$, $w_h \in C(\Omega_0)$,

$$\begin{aligned} & |K_h * \partial_h^\alpha w_h - D^\alpha w|_{\Omega_2} \\ & \leq C \left\{ h^{2r-2} |w|_{2r-2+|\alpha|, \Omega_1} + \sum_{|\beta| \leq r-2+N_0} \|\partial_h^{\alpha+\beta}(w_h - w)\|_{-(r-2), \Omega_1} \right. \\ & \qquad \qquad \qquad \left. + h^{r-2} \sum_{|\beta| \leq r-2} |\partial_h^{\alpha+\beta}(w_h - w)|_{\Omega_1} \right\}. \end{aligned}$$

Applying this to $w_h = D_t^l u_h$ and $w = D_t^l u$ we obtain by the negative norm estimate (4.4) and the maximum norm estimate (4.3) that for $\Omega_1 \subset\subset \Omega_0$, $0 < t_* \leq t \leq t^*$,

$$(4.16) \quad |K_h * \partial_h^\alpha D_t^l u_h - D_x^\alpha D_t^l u|_{\Omega_1} \leq Ch^{2r-2} \|v\|_{r-2}.$$

For $\alpha = l = 0$ this was Theorem 7.2 of [3].

We can now show that this high order estimate in space is not spoiled by discretizing in time.

THEOREM 4.3. *Under the assumptions of Theorem 4.1, with $K_h = K_h^{(\alpha)}$ as in*

Lemma 4.3, we have for any $\Omega_1 \subset\subset \Omega_0$, $0 < t_* \leq t = nk \leq t^*$,

$$|K_h * \partial_h^\alpha q_k U^n - D_x^\alpha D_t^l \mu(nk)|_{\Omega_1} \leq C\{h^{2r-2} \|v\|_{r-2} + k^\nu \|v\|\}.$$

Proof. We have by Theorem 4.1, with $\Omega_1 \subset\subset \Omega'_1 \subset\subset \Omega_0$,

$$|K_h * \partial_h^\alpha (q_k U^n - D_t^l \mu_h(nk))|_{\Omega_1} \leq C|\partial_h^\alpha (q_k U^n - D_t^l \mu_h(nk))|_{\Omega'_1} \leq Ck^\nu \|v\|.$$

In view of (4.16) this proves the theorem.

5. Examples. In this section we present examples of schemes defined by the four classes of rational functions I, II, III and IV and discuss their computational implementation, in particular in the case when T_h is defined by means of a bilinear form (cf. [3, Section 8]),

$$(5.1) \quad B_h(T_h f, \chi) = (f, \chi), \quad \forall \chi \in S_h.$$

As was pointed out in the introduction, since T_h rather than $L_h = T_h^{-1}$ is given in applications, it is now natural to study $r(kL_h)$ as a rational function of T_h , or equivalently, to consider the rational function $r(k/\mu)$ of μ .

Padé Schemes. Examples of rational functions of types I, II and IV are provided by the above diagonal, diagonal and below diagonal entries of the Padé table for $e^{-\tau}$, respectively. In fact, the general entry in this Padé table is given by

$$r_{p,q}(\tau) = n_{p,q}(\tau)/d_{p,q}(\tau),$$

where

$$(5.2) \quad n_{p,q}(\tau) = \sum_{j=0}^q \frac{(p+q-j)!q!}{(p+q)!j!(q-j)!} (-1)^j \tau^j,$$

and

$$(5.3) \quad d_{p,q}(\tau) = \sum_{j=0}^p \frac{(p+q-j)!p!}{(p+q)!j!(p-j)!} \tau^j.$$

By the definition of the Padé approximant,

$$(5.4) \quad r_{p,q}(\tau) = e^{-\tau} + O(\tau^{p+q+1}) \quad \text{as } \tau \rightarrow 0,$$

so that (1.7) holds with $\nu = p + q$. It is well known and obvious from (5.2) and (5.3) that $r_{p,q}$ is of type II and IV for $p = q$ and $p > q$, respectively, and clearly, by (5.4), $r_{p,q}$ is of type I for $p < q$.

In particular, we have $r_{0,1}(\tau) = 1 - \tau$, which is a rational function of type I with $\alpha = 1$. This defines

$$U^{n+1} = U^n - kL_h U^n,$$

and with (5.1),

$$(U^{n+1}, \chi) = (U^n, \chi) - kB_h(U^n, \chi), \quad \forall \chi \in S_h.$$

If B_h is bounded in $H^1(\Omega)$ and the inverse assumption

$$\|\chi\|_{H^1(\Omega)} \leq Ch^{-1}\|\chi\|, \quad \forall \chi \in S_h,$$

holds, then we have

$$(L_h \chi, \chi) = B_h(\chi, \chi) \leq C_1 \|\chi\|_{H^1(\Omega)}^2 \leq C_2 h^{-2} \|\chi\|^2,$$

so that for the maximum eigenvalue of L_h ,

$$\Lambda_{\max} \leq C_2 h^{-2}.$$

Hence, a type I' scheme is defined here for

$$k/h^2 \leq \alpha_0/C_2 \quad \text{with } \alpha_0 < 1.$$

The subdiagonal and diagonal Padé approximants with linear denominators are

$$r_{1,0}(\tau) = \frac{1}{1 + \tau} \quad \text{and} \quad r_{1,1}(\tau) = \frac{1 - \frac{1}{2}\tau}{1 + \frac{1}{2}\tau},$$

which are of types IV and II, respectively. They correspond respectively to the purely implicit scheme

$$(U^{n+1}, \chi) + kB_h(U^{n+1}, \chi) = (U^n, \chi), \quad \forall \chi \in S_h,$$

and the trapezoidal (Crank-Nicolson) scheme

$$(U^{n+1}, \chi) + \frac{1}{2}kB_h(U^{n+1}, \chi) = (U^n, \chi) - \frac{1}{2}kB_h(U^n, \chi), \quad \forall \chi \in S_h.$$

We consider also the subdiagonal and diagonal Padé approximants with quadratic denominators,

$$r_{2,0}(\tau) = \frac{1}{1 + \tau + \frac{1}{2}\tau^2}, \quad r_{2,1}(\tau) = \frac{1 - \frac{1}{3}\tau}{1 + \frac{2}{3}\tau + \frac{1}{6}\tau^2},$$

and

$$r_{2,2}(\tau) = \frac{1 - \frac{1}{2}\tau + \frac{1}{12}\tau^2}{1 + \frac{1}{2}\tau + \frac{1}{12}\tau^2}.$$

In all of these cases the poles are complex. Hence in the use of these functions to obtain the time stepping procedure it is convenient to use complex matrices even though the approximations U^n will be real. We shall see now that it is sufficient to solve one complex system at each time.

Consider first $r_{2,1}$. Setting

$$\beta_1 = \frac{1}{3} \left(1 + i\frac{\sqrt{2}}{2} \right), \quad \gamma_1 = 1 - i\frac{\sqrt{2}}{2}$$

we have

$$r_{2,1}(k/\mu) = \frac{\mu^2 - \frac{1}{3}k\mu}{\mu^2 + \frac{2}{3}k\mu + \frac{1}{6}k^2} = 1 - k \operatorname{Re}\left(\frac{\gamma_1}{\mu + \beta_1 k}\right),$$

and hence, with $A_h = T_h + k\beta_1 I$, (1.7) reduces to

$$U^{n+1} = U^n - k \operatorname{Re}(\gamma_1 A_h^{-1} U^n),$$

where A_h^{-1} exists since $\operatorname{Re} \beta_1 > 0$. Note that in order to compute $W = k\gamma_1 A_h^{-1} U^n$ we solve the complex elliptic problem

$$(W, \chi) + k\beta_1 B_h(W, \chi) = k\gamma_1 B_h(U^n, \chi), \quad \forall \chi \in S_h,$$

which amounts to solving a nondegenerate complex linear system of equations.

The analogous statements for $r_{2,0}$ and $r_{2,2}$ follow from

$$r_{2,0}(k/\mu) = \frac{\mu^2}{\mu^2 + k\mu + \frac{1}{2}k^2} = 1 - k \operatorname{Re}\left(\frac{1}{\mu + \beta_0 k}\right)$$

and

$$r_{2,2}(k/\mu) = \frac{\mu^2 - \frac{1}{2}\mu k + \frac{1}{12}k^2}{\mu^2 + \frac{1}{2}\mu k + \frac{1}{12}k^2} = 1 - k \operatorname{Re}\left(\frac{\gamma_2}{\mu + \beta_2 k}\right),$$

where

$$\beta_0 = \frac{1}{2}(1 + i), \quad \beta_2 = \frac{1}{4}(1 + i\sqrt{3}/3), \quad \gamma_2 = 1 - i\sqrt{3}.$$

We shall now turn to the schemes of type III and IV mentioned in the introduction, for which the rational functions employed have denominators a power of $(1 + b\tau)$ with b positive. For their analysis we shall use some simple properties of Laguerre polynomials.

Recall that the Laguerre polynomials $\{L_n^\alpha\}$ of order $\alpha, \alpha > -1$,

$$L_n^\alpha(x) = (n + \alpha)! \sum_{j=0}^n \frac{(-1)^j x^j}{j!(n-j)!(j + \alpha)!},$$

are the polynomials which are orthogonal with respect to the weight function $x^\alpha e^{-x}$ on $(0, \infty)$. For their generating function we have

$$(5.5) \quad (1 - t)^{-1-\alpha} e^{-xt/(1-t)} = \sum_{n=0}^{\infty} L_n^\alpha(x) t^n \quad \text{for } |t| < 1, x \geq 0.$$

We recall also the three term recursion formula

$$(5.6) \quad nL_n^\alpha(x) = (-x + 2n + \alpha - 1)L_{n-1}^\alpha(x) - (n + \alpha - 1)L_{n-2}^\alpha(x),$$

and finally the relation

$$(5.7) \quad \frac{d}{dx} L_n^\alpha(x) = x^{-1} \{nL_n^\alpha(x) - (n + \alpha)L_{n-1}^\alpha(x)\}, \quad n \geq 1.$$

Some Type III Schemes. Setting $\tau = xt/(1 - t)$ in (5.5) with $\alpha = 1$ we obtain

$$e^{-\tau} = (1 - t)^2 \sum_{n=0}^{\infty} L_n^1(x)t^n,$$

and hence, using also the recursion relation (5.6),

$$e^{-\tau} = 1 - \sum_{n=0}^{\infty} \frac{xL_n^1(x)}{n+1} t^{n+1} = 1 - \sum_{n=0}^{\infty} \frac{xL_n^1(x)}{n+1} \left(\frac{\tau}{x+\tau}\right)^{n+1}.$$

Consequently, with $b = 1/x$ any positive number, we have

$$(5.8) \quad e^{-\tau} = 1 - \sum_{n=0}^{\infty} P_n(b) \left(\frac{\tau}{1+b\tau}\right)^{n+1} \quad \text{for } \tau > 0,$$

where P_n is the polynomial of degree n defined by

$$P_n(b) = (n+1)^{-1} b^n L_n^1(1/b).$$

Note that since L_n^1 has its zeros positive and distinct the same holds for P_n .

Now let $b_n = 1/\beta_n$ denote the largest zero of P_n (so that β_n is the smallest zero of L_n^1). We define for $\nu \geq 2$ the rational function

$$r_\nu(\tau) = 1 - \sum_{j=0}^{\nu-2} P_j(b_{\nu-1}) \left(\frac{\tau}{1+b_{\nu-1}\tau}\right)^{j+1}.$$

In view of (5.8) and the choice of $b_{\nu-1}$ it is obvious that

$$r_\nu(\tau) = e^{-\tau} + O(\tau^{\nu+1}) \quad \text{as } \tau \rightarrow 0.$$

In order to see that these rational functions are of type III for $\nu \geq 3$ we shall establish that for those ν ,

$$(5.9) \quad \sup_{\tau > \delta} |r_\nu(\tau)| < 1 \quad \text{for any } \delta > 0.$$

Since $r_\nu(\tau)$ is decreasing it suffices to show

$$\lim_{\tau \rightarrow \infty} r_\nu(\tau) > -1.$$

But, with $\beta_j = 1/b_j$, we have

$$\begin{aligned} \lim_{\tau \rightarrow \infty} r_\nu(\tau) &= 1 - \sum_{j=0}^{\nu-2} P_j(b_{\nu-1}) b_{\nu-1}^{-(j+1)} \\ &= 1 - \beta_{\nu-1} \sum_{j=0}^{\nu-2} \frac{L_j^1(\beta_{\nu-1})}{j+1} = f_\nu, \end{aligned}$$

and we shall prove that for $\nu \geq 2$, $f_{\nu+1} > f_\nu$. Since $f_2 = 1 - \beta_1 = 1 - 2 = -1$, this will complete the proof. Set

$$f(\beta) = 1 - \beta \sum_{j=0}^{\nu-1} \frac{L_j^1(\beta)}{j+1},$$

so that

$$f_\nu = f(\beta_{\nu-1}), \quad f_{\nu+1} = f(\beta_\nu).$$

Since $\beta_{j-1} > \beta_j$ it suffices to show that $f(\beta)$ is decreasing in $(0, \beta_{\nu-1})$. But, using (5.7) with $\alpha = 1$ we obtain

$$f'(\beta) = -1 - \sum_{j=1}^{\nu-1} (L_j^1(\beta) - L_{j-1}^1(\beta)) = -L_{\nu-1}^1(\beta),$$

which is negative in $(0, \beta_{\nu-1})$. This completes the proof of (5.9).

We shall now consider the computational implementation of the scheme corresponding to these rational functions. We have

$$r_\nu(k/u) = 1 - \sum_{j=0}^{\nu-2} k^{j+1} P_j(b_{\nu-1}) \frac{1}{(\mu + kb_{\nu-1})^{j+1}},$$

so that with $A_h = T_h + kb_{\nu-1}I$, (1.7) reduces to

$$U^{n+1} = U^n - \sum_{j=0}^{\nu-2} k^{j+1} P_j(b_{\nu-1}) A_h^{-(j+1)} U^n.$$

Setting

$$U_0^n = U^n, \quad U_{j+1}^n = kA_h^{-1} U_j^n,$$

we find

$$U^{n+1} = U^n - \sum_{j=0}^{\nu-2} P_j(b_{\nu-1}) U_{j+1}^n.$$

Hence U^{n+1} can be obtained from U^n by solving $\nu - 1$ linear systems, all with the same matrix A_h . When T_h is defined by (5.1) this system takes the form

$$(U_{j+1}^n, \chi) + kb_{\nu-1} B_h(U_{j+1}^n, \chi) = kB_h(U_j^n, \chi), \quad \forall \chi \in S_h.$$

For $\nu = 2$ we obtain

$$r_2(\tau) = 1 - \frac{\tau}{1 + \frac{1}{2}\tau} = \frac{1 - \frac{1}{2}\tau}{1 + \frac{1}{2}\tau},$$

which defines the trapezoidal type II scheme discussed above. For $\nu = 3$, we have

$$r_3(\tau) = 1 - \frac{\tau}{1 + b_2\tau} - \frac{\sqrt{3}}{6} \left(\frac{\tau}{1 + b_2\tau} \right)^2, \quad b_2 = \frac{1}{2} \left(1 + \frac{\sqrt{3}}{3} \right),$$

which corresponds to the Calahan scheme analyzed by Zlámál [15]. In the appendix we have listed the coefficients for the schemes with $\nu \leq 10$.

Some Type IV Schemes. In a way analogous to the derivation of the type III schemes above we can generate a class of type IV schemes. By taking $\alpha = 0$ in (5.5) and making the same subsequent change of variables as above, we have that for $b > 0$,

$$e^{-\tau} = \frac{1}{1 + b\tau} \sum_{j=0}^{\infty} Q_j(b) \left(\frac{\tau}{1 + b\tau} \right)^j \quad \text{for } \tau \geq 0,$$

where $Q_j(b) = b^j L_j^0(1/b)$. Defining now for $\nu \geq 1$,

$$r_\nu(\tau) = \frac{1}{1 + b_\nu\tau} \sum_{j=0}^{\nu-1} Q_j(b_\nu) \left(\frac{\tau}{1 + b_\nu\tau} \right)^j$$

where b_ν is the largest zero of Q_ν , we clearly have

$$r_\nu(\tau) = e^{-\tau} + O(\tau^{\nu+1}) \quad \text{as } \tau \rightarrow 0.$$

In order to show that $r_\nu(\tau)$ induces a type IV scheme it remains only to establish that

$$0 < r_\nu(\tau) < 1 \quad \text{for } \tau > 0,$$

since clearly $\lim_{\tau \rightarrow \infty} r_\nu(\tau) = 0$. Setting, as above, $\beta_j = 1/b_j$ we have

$$r_\nu(\tau) = \frac{1}{1 + b_\nu \tau} \sum_{j=0}^{\nu-1} L_j^0(\beta_\nu) \left(\frac{\tau b_\nu}{1 + \tau b_\nu} \right)^j,$$

and hence, with $\tau b_\nu / (1 + \tau b_\nu) = \lambda$ it is enough to prove that for each λ in $(0, 1)$,

$$0 < f(\lambda) = (1 - \lambda) \sum_{j=0}^{\nu-1} L_j^0(\beta_\nu) \lambda^j < 1.$$

Since $f(0) = 1$ and $f(1) = 0$ it suffices to show that f is decreasing in $(0, 1)$. But, using (5.7) in the last step we obtain

$$\begin{aligned} f'(\lambda) &= \sum_{j=1}^{\nu-1} j L_j^0(\beta_\nu) \lambda^{j-1} - \sum_{j=0}^{\nu-1} (j+1) L_j^0(\beta_\nu) \lambda^j \\ &= \sum_{j=1}^{\nu-1} j(L_j^0(\beta_\nu) - L_{j-1}^0(\beta_\nu)) \lambda^{j-1} - \nu L_{\nu-1}^0(\beta_\nu) \lambda^{\nu-1} \\ &= \sum_{j=1}^{\nu-1} \beta_\nu \frac{d}{dx} L_j^0(\beta_\nu) \lambda^{j-1} - \nu L_{\nu-1}^0(\beta_\nu) \lambda^{\nu-1}. \end{aligned}$$

Since L_j^0 is nonincreasing in $(0, \beta_j)$ and $L_{\nu-1}^0(\beta_\nu)$ is positive, the result follows.

We have here

$$r_\nu(k/\mu) = \frac{\mu}{\mu + b_\nu k} \sum_{j=0}^{\nu-1} k^j Q_j(b_\nu) \frac{1}{(\mu + kb_\nu)^j},$$

so that now with $A_h = T_h + kb_\nu I$, (1.6) reduces to

$$U^{n+1} = \sum_{j=0}^{\nu-1} Q_j(b_\nu) U_j^n,$$

where the U_j^n 's are defined by

$$U_0^n = A_h^{-1} T_h U^n, \quad U_{j+1}^n = k A_h^{-1} U_j^n, \quad j = 0, \dots, \nu - 2.$$

When T_h is defined by (5.1), this is

$$\begin{aligned} (U_0^n, \chi) + kb_\nu B_h(U_0^n, \chi) &= (U^n, \chi), \quad \forall \chi \in S_h, \\ (U_{j+1}^n, \chi) + kb_\nu B_h(U_{j+1}^n, \chi) &= kB_h(U_j^n, \chi), \quad j = 0, \dots, \nu - 2. \end{aligned}$$

The values of b_ν and $Q_j(b_\nu)$ for $0 \leq j \leq \nu - 1$ and $\nu \leq 10$ are given in the appendix.

6. Variations. In this section we shall briefly focus our attention first on schemes in which both the time and space discretizations are allowed to change a finite number of times and then where initial data other than P_0v are chosen.

We consider thus a finite set of rational functions $\{r_j(\tau)\}_1^M$, a corresponding set of time steps $\{k_j\}_1^M$ and a finite set of finite dimensional subspaces $\{S_{j,h_j}\}_1^M$ of $L_2(\Omega)$ with corresponding operators T_{j,h_j} and $L_{j,h_j} = T_{j,h_j}^{-1}$. Denoting the L_2 projection onto S_{j,h_j} by $P_{j,0}$ we then define a discretization scheme by successively applying the j th scheme n_j times with time step k_j , for $j = 1, \dots, M$. More precisely, setting $U_j^n \in S_{j,h_j}$, $n = 0, \dots, n_j$, the approximation at $t = \sum_{i=1}^{j-1} n_i k_i + nk_j = t_{j-1} + nk_j$ (with $t_0 = 0$), we define

$$U_j^n = r_j(k_j L_{j,h_j})^n P_{j,0} U_{j-1}^{n-1} \quad \text{for } n = 0, \dots, n_j,$$

$$U_1^0 = P_{1,0} v.$$

We then have the following L_2 error estimates:

THEOREM 6.1. *Assume that each of the schemes is of type I' or II. Then for $0 \leq t = \sum_{i=1}^{j-1} n_i k_i + nk_j \leq t^*$, $n = 1, \dots, n_j$, $j = 1, \dots, M$,*

$$(6.1) \quad \|U_j^n - u(t)\| \leq C \sum_{j=1}^M \{h_j^r \|v\|_{r_j} + k_j^v \|v\|_{2\nu_j}\}.$$

Further, if $t_1 = n_1 k_1 \geq t_*$ and $0 < t_* \leq t = \sum_{i=1}^{j-1} n_i k_i + nk_j \leq t^*$ then

$$(6.2) \quad \|U_j^n - u(t)\| \leq C(t_*) \sum_{j=1}^n (h_j^r + k_j^v) \|v\|.$$

Proof. We denote by \tilde{U}_j^n the fully discrete Galerkin approximation at time $t = t_{j-1} + nk_j$ with initial values $u(t_{j-1})$ for $n = 0$, that is

$$\tilde{U}_j^n = r_j(k_j L_{j,h_j})^n P_{j,0} u(t_{j-1}), \quad n = 0, \dots, n_j.$$

We then have, by Theorem 2.2, for $n = 1, \dots, n_j$,

$$\|\tilde{U}_j^n - u(t_{j-1} + nk_j)\| \leq C \{h_j^r \|u(t_{j-1})\|_{r_j} + k_j^v \|u(t_{j-1})\|_{2\nu_j}\}.$$

In particular, setting $j = 1$ this shows (6.1) for $t \leq t_1$. For $t > t_1$, on the other hand, using the stability of the scheme (cf. (1.11)),

$$\|U_j^n - \tilde{U}_j^n\| \leq \|U_{j-1}^{n-1} - u(t_{j-1})\|,$$

so that

$$(6.3) \quad \|U_j^n - u(t_{j-1} + nk_j)\| \leq \|U_{j-1}^{n-1} - u(t_{j-1})\| + C \{h_j^r \|u(t_{j-1})\|_{r_j} + k_j^v \|u(t_{j-1})\|_{2\nu_j}\}.$$

Now, since the solution operator of the continuous problem is bounded in \dot{H}^s , we obtain

$$\|U_j^n - u(t_{j-1} + nk_j)\| \leq \|U_{j-1}^{n-1} - u(t_{j-1})\| + C \{h_j^r \|v\|_{r_j} + k_j^v \|v\|_{2\nu_j}\}.$$

The first result (6.1) now follows at once by recursion.

In order to prove (6.2) we use the fact that for any $s \geq 0$, and $t \geq t_*$,

$$\|u(t)\|_s \leq Ct^{-s/2} \|v\| \leq C(t_*) \|v\|,$$

so that (6.3) implies for $j = 2, \dots, M$,

$$\begin{aligned} \|U_j^n - u(t_{j-1} + nk_j)\| \\ \leq \|U_{j-1}^{n_{j-1}} - u(t_{j-1})\| + C(t_*)(h_j^r + k_j^\nu) \|v\|. \end{aligned}$$

Since now by Theorem 2.1,

$$\|U_1^{n_1} - u(t_1)\| \leq C(t_*)(h_1^r + k_1^\nu) \|v\|,$$

the result (6.2) also follows by recursion. This completes the proof.

Let us notice that if only the time discretization varies and not the spaces $\{S_{j,h_j}\}$ then with T_h and $L_h = T_h^{-1}$ corresponding to S_h , we have

$$U_j^n = \prod_{l=1}^{j-1} r(k_l L_h)^{n_l} r(k_j L_h)^n P_0 v,$$

where now the operators in the product commute. Consequently, the order in which the time discretizations have been applied is insignificant. It follows, for instance, that the finitely many different time discretizations can be applied cyclically, to give the analogues of the results of (6.1) and (6.2), the latter for any time bounded away from zero and infinity.

We now return to the completely discrete problem (1.7), but with initial data v_h other than $P_0 v$, so that

$$U^n = r(k L_h)^n v_h.$$

Following the lines of the proof of Theorem 3.3 in [3] we then have the following L_2 error estimate:

THEOREM 6.2. *Assume that the scheme is of type I', II' or III. Then for each $j \geq 0$ and for $0 < t = nk \leq t^*$,*

$$\|U^n - u(nk)\| \leq C(h^r t^{-r/2} + k^\nu t^{-\nu}) \|v_h\| + Ct^{-j/2} \|v - v_h\|_{-j}.$$

Proof. Let \tilde{u} be the solution of the continuous problem with initial data v_h . Then by Theorem 2.2,

$$\|U^n - \tilde{u}(nk)\| \leq C\{h^r t^{-r/2} + k^\nu t^{-\nu}\} \|v_h\|.$$

On the other hand, since $u - \tilde{u}$ is the solution of the continuous problem with initial data $v - v_h$ we have

$$\|u(t) - \tilde{u}(t)\| \leq Ct^{-j/2} \|v - v_h\|_{-j}.$$

Together these estimates prove the theorem.

In particular, if v_h is chosen boundedly in L_2 and approximating v to order $O(h^r)$ in some negative norm, the error is $O(h^r + k^\nu)$ for t positive. Recall from [3] that this is satisfied, for example, for v_h the elliptic projection $P_1 v = T_h L v$ of $v \in \dot{H}^2$ if (iib) (or (iia) if $r = 2$) holds.

Appendix

(a) Tables of constants associated with the rational functions $r_\nu(\tau) = 1 - \sum_{j=0}^{\nu-2} P_j(b_{\nu-1})(\tau/(1 + b_{\nu-1}\tau))^{j+1}$, $\nu \leq 10$, rounded to eight figures.

$P_0 \equiv 1.$

$b_1 = .5$

$b_2 = .78867513$

| j | $P_j(b_2)$ |
|-----|------------|
| 1 | .28867513 |

$b_3 = 1.0685790$

| j | $P_j(b_3)$ |
|-----|------------|
| 1 | .56857902 |
| 2 | .23994877 |

$b_4 = 1.3453664$

| j | $P_j(b_4)$ |
|-----|------------|
| 1 | .84536642 |
| 2 | .63131105 |
| 3 | .35112809 |

$b_5 = 1.6206645$

| j | $P_j(b_5)$ |
|-----|------------|
| 1 | 1.1206645 |
| 2 | 1.1725556 |
| 3 | 1.0855973 |
| 4 | .75003511 |

$b_6 = 1.8951306$

| j | $P_j(b_6)$ |
|-----|------------|
| 1 | 1.3951306 |
| 2 | 1.8630560 |
| 3 | 2.3250180 |
| 4 | 2.5702151 |
| 5 | 2.1228872 |

$b_7 = 2.1690834$

| j | $P_j(b_7)$ |
|-----|------------|
| 1 | 1.6690834 |
| 2 | 2.7025062 |
| 3 | 4.1908611 |
| 4 | 6.0773015 |
| 5 | 7.8122875 |
| 6 | 7.5096538 |

$b_8 = 2.4426969$

| j | $P_j(b_8)$ |
|-----|------------|
| 1 | 1.9426969 |
| 2 | 3.6907381 |
| 3 | 6.8045360 |
| 4 | 12.020296 |
| 5 | 19.865792 |
| 6 | 29.119416 |
| 7 | 31.936476 |

$b_9 = 2.7160742$

| j | $P_j(b_9)$ |
|-----|------------|
| 1 | 2.2160742 |
| 2 | 4.8276516 |
| 3 | 10.287422 |
| 4 | 21.280435 |
| 5 | 42.191381 |
| 6 | 78.287509 |
| 7 | 128.88852 |
| 8 | 158.83591 |

(b) Tables of constants associated with the rational functions $r_\nu(\tau) = [1/(1 + b_\nu\tau)] \sum_{j=0}^{\nu-1} Q_j(b_\nu)(\tau/(1 + b_\nu\tau))^j$, $\nu \leq 10$, rounded to eight figures.

$Q_0 \equiv 1.$

$b_6 = 4.4873917$

$b_9 = 6.5650300$

$b_1 = 1$

| j | $Q_j(b_6)$ |
|-----|------------|
| 1 | 3.4873917 |
| 2 | 11.661901 |
| 3 | 36.515558 |
| 4 | 101.50142 |
| 5 | 211.31583 |

| j | $Q_j(b_9)$ |
|-----|------------|
| 1 | 5.5650300 |
| 2 | 30.469559 |
| 3 | 163.33232 |
| 4 | 850.73985 |
| 5 | 4251.4423 |
| 6 | 19905.841 |
| 7 | 82793.242 |
| 8 | 258096.14 |

$b_2 = 1.7071068$

| j | $Q_j(b_2)$ |
|-----|------------|
| 1 | .70710678 |

$b_3 = 2.4051496$

| j | $Q_j(b_3)$ |
|-----|------------|
| 1 | 1.4051496 |
| 2 | 1.4744453 |

$b_7 = 5.1801749$

| j | $Q_j(b_7)$ |
|-----|------------|
| 1 | 4.1801749 |
| 2 | 16.973862 |
| 3 | 66.106869 |
| 4 | 241.14213 |
| 5 | 781.11612 |
| 6 | 1895.6814 |

$b_{10} = 7.2572379$

$b_4 = 3.1003167$

| j | $Q_j(b_4)$ |
|-----|------------|
| 1 | 2.1003167 |
| 2 | 3.9113304 |
| 3 | 5.4480493 |

| j | $Q_j(b_{10})$ |
|-----|---------------|
| 1 | 6.2572379 |
| 2 | 38.653026 |
| 3 | 234.93728 |
| 4 | 1398.1894 |
| 5 | 8086.1025 |
| 6 | 44871.439 |
| 7 | 233319.27 |
| 8 | 1077827.0 |
| 9 | 3732247.5 |

$b_5 = 3.7941979$

| j | $Q_j(b_5)$ |
|-----|------------|
| 1 | 2.7941979 |
| 2 | 7.3075442 |
| 3 | 16.957853 |
| 4 | 29.458888 |

$b_8 = 5.8726930$

| j | $Q_j(b_8)$ |
|-----|------------|
| 1 | 4.8726930 |
| 2 | 23.243137 |
| 3 | 107.71731 |
| 4 | 478.88829 |
| 5 | 1994.4686 |
| 6 | 7377.7839 |
| 7 | 20451.648 |

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