THE AUXILIARY SPACE PRECONDITIONER FOR THE DE RHAM COMPLEX

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ABSTRACT. We generalize the construction and analysis of auxiliary space preconditioners to the \( n \)-dimensional finite element subcomplex of the de Rham complex. These preconditioners are based on a generalization of a decomposition of Sobolev space functions into a regular part and a potential. A discrete version is easily established using the tools of finite element exterior calculus. We then discuss the four-dimensional de Rham complex in detail. By identifying forms in four dimensions (4D) with simple proxies, form operations are written out in terms of familiar algebraic operations on matrices, vectors, and scalars. This provides the basis for our implementation of the preconditioners in 4D. Extensive numerical experiments illustrate their performance, practical scalability, and parameter robustness, all in accordance with the theory.

1. INTRODUCTION

The auxiliary space preconditioners for problems posed in \( H(\text{curl}) \) and \( H(\text{div}) \), initiated by Hiptmair and Xu [21], are now well understood both theoretically and practically, in two and three space dimensions. These preconditioners have been used for accelerating a wide variety of solution techniques, thanks to their highly scalable parallel implementations, known as AMS and ADS preconditioners (see the software libraries HYPRE [22] and MFEM [30]). The goal of the present work is two-fold. First, we generalize the mathematical design and analysis of these preconditioners to \( n \) dimensions. Second, we provide an implementation of the preconditioners in 4D and detail the techniques we used to transform 4D exterior calculus into matrix and vector operations.

An important ingredient in the analysis of the auxiliary space preconditioners in two and three dimensions was the so-called regular decomposition, which splits a Sobolev space function into a component with higher regularity and a scalar or vector potential. Such decompositions were known early on [8]. But the key to the success of the auxiliary space preconditioners was a discrete version of this decomposition found in [21], now also known as the HX decomposition. Its practical use was elaborated in [26] and [27], where slightly stronger results were established (using [35]) to prove robustness of the solvers in a general setting involving a stiffness term and a mass term weighted with a parameter. Further solvers in \( H(\text{curl}) \) and \( H(\text{div}) \) were developed in [9] and [10].

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One of the motivations for this work, especially our 4D implementation, is the recent increased interest in spacetime discretizations. In three space dimensions, they yield large linear systems built on 4D meshes and discretizations. Starting as early as the eighties, literature on spacetime methods began to accumulate [4, 5, 17, 24, 25, 42]. As methods that parallelize only spatial degrees of freedom created increasingly larger computational bottlenecks in temporal simulations [14], the potential for higher scalability of the spacetime methods received more attention, resulting in a resurgence of interest in recent years [1, 5, 6, 28, 29, 31, 33, 34, 37, 38, 39, 40, 41]. Further reasons for pursuing spacetime discretizations, such as limited regularity [13] and spacetime adaptivity [16] have also been noted.

Among these reasons, the most relevant to this work is the above-mentioned potential of spacetime methods to break through temporal causality barriers when exploiting parallelism. However, this potential is unlikely to be realized without highly scalable solvers. In turn, spacetime solvers in 4D are unlikely to be developed without a complete understanding of preconditioners for the norm generated by each of the four canonical first order partial differential operators in 4D. Herein lies one of our contributions. We show how to precondition the norm of all the first order Sobolev spaces in 4D. We thus provide building blocks for designing future solvers for more complex spacetime partial differential equations.

The remainder of the paper is structured as follows. We begin in Section 2 with the necessary background on finite element exterior calculus and introduce the regular decomposition in \( n \)-dimensions. This section also reviews a few new tools available thanks to the recent intensive research on finite element exterior calculus, such as the bounded cochain projections and the canonical interpolation operators, along with their commutativity and approximation properties. Section 3, introduces the auxiliary space preconditioner, which is the main object of this study. After its definition and complete analysis, we proceed to Section 4, which specializes the discussion to 4D exterior calculus and presents techniques and identities used for the implementation of the preconditioner and its 4D ingredients. Section 5 contains a large set of numerical results illustrating the scalable and robust performance of the method all in accordance with the theory.

2. Preliminaries

We use finite element exterior calculus, for which standard references include [3, 19]. In this section, we establish the exterior calculus notations used in this paper and recall results pertinent for the analysis of preconditioners.

2.1. Sobolev spaces of exterior forms. First, we set notations for \( k \)-forms in \( n \)-dimensions (\( 0 \leq k \leq n \)). The set of increasing multi-indices with \( k \) components is denoted by \( \mathcal{I}_k = \{ \alpha = (\alpha_1, \ldots, \alpha_k) : 1 \leq \alpha_1 < \alpha_2 < \cdots < \alpha_k \leq n \} \). For \( \alpha \in \mathcal{I}_k \) and \( x = (x^1, x^2, \ldots, x^n) \), we abbreviate the elementary \( k \)-form \( dx^{\alpha_1} \wedge dx^{\alpha_2} \wedge \cdots \wedge dx^{\alpha_k} \) to simply \( dx^{\alpha} \). The space of \( k \)-forms on \( \mathbb{R}^n \) is denoted by \( \Lambda^k = \{ \sum_{\alpha \in \mathcal{I}_k} c_\alpha dx^\alpha : c_\alpha \in \mathbb{R} \} \) and its dimension is \( n_k \equiv \binom{n}{k} \). Let \( H^s(\Omega) \) denote the standard Sobolev space on any open \( \Omega \subset \mathbb{R}^n \). The Sobolev space of exterior \( k \)-forms is defined by

\[
H^s(\Omega, \Lambda^k) = \left\{ w = \sum_{\alpha \in \mathcal{I}_k} w_\alpha(x) \, dx^\alpha : w_\alpha \in H^s(\Omega) \right\}.
\]
Its norm is given by
\[ \|w\|_{H^s(\Omega, \Lambda^k)}^2 = \sum_{\alpha \in I_k} \|w_\alpha\|_{H^s(\Omega)}^2. \] (1)

The above notation scheme generalizes to analogously define other spaces of forms like \( L^2(\Omega, \Lambda^k) \), \( C(\Omega, \Lambda^k) \), etc. Thus \( \mathcal{D}'(\Omega, \Lambda^k) \) denotes the space of \( k \)-forms whose components \( \varphi_{i_1 \cdots i_k} \) are distributions in \( \mathcal{D}'(\Omega) \) (where \( \mathcal{D}(\Omega) \) is the space of smooth compactly supported test functions). The inner product and norm of \( L^2(\Omega, \Lambda^k) \) is denoted simply by \((\cdot, \cdot)\) and \( \| \cdot \| \), respectively. In either case the form degree \( k \) will be understood from context.

Let \( d \equiv d^{(k)} \) denote the \( k \)th exterior derivative, e.g., when applied to \( w = w_\alpha dx^\alpha \in H^1(\Omega, \Lambda^k) \), the exterior derivative \( dw \) is given by
\[ dw = \sum_{i=1}^n \partial_i w_\alpha \, dx^i \wedge dx^\alpha, \] (2)
where \( \partial_i w_\alpha \) is the usual \( i \)th partial derivative \( \partial w_\alpha / \partial x^i \) of the scalar multivariate function \( w_\alpha \). In three dimensions, \( d^0 \) generates the familiar gradient, \( d^1 \) generates curl, and \( d^2 \) generates the divergence operator. In four dimensions, the exterior derivative has analogous interpretations, which are worked out in detail later in \$4.1$.

We are interested in the Sobolev spaces
\[ H(d, \Omega, \Lambda^k) = \{ w \in L^2(\Omega, \Lambda^k) : dw \in L^2(\Omega, \Lambda^{k+1}) \} \]
normed by
\[ \|w\|_{H(d, \Omega, \Lambda^k)}^2 = \|w\|^2 + \|dw\|^2. \]

2.2. Regular decomposition. From now on, within this section, we tacitly assume that \( \Omega \) is an open bounded domain that is starlike with respect to a ball \( B \), by which we mean that for any \( x \in \Omega \), the convex hull of \( x \) and \( B \) is contained in \( \Omega \). This assumption implies that topology of \( \Omega \) is trivial, i.e., \( \Omega \) is homotopy equivalent to a ball, and that the boundary of \( \Omega \) is Lipschitz. Under this assumption the results of [12] give regular potentials, which we use below to construct a decomposition of \( H(d, \Omega, \Lambda^k) \) into a smooth (or regular) part and a remaining potential.

**Theorem 1** (Regular decomposition). For each integer \( 1 \leq k \leq n \), there is a \( C_1 > 0 \) and continuous linear maps
\[ S : H(d, \Omega, \Lambda^k) \to H^1(\Omega, \Lambda^k), \quad P : H(d, \Omega, \Lambda^k) \to H^1(\Omega, \Lambda^{k-1}) \]
such that
\[ w = Sw + dPw \quad \forall w \in H(d, \Omega, \Lambda^k) \]
and
\[ \|Sw\|_{H^1(\Omega, \Lambda^k)} \leq C_1 \|dw\|_{L^2(\Omega, \Lambda^{k+1})}, \quad \|Pw\|_{H^1(\Omega, \Lambda^{k-1})} \leq C_1 \|w\|_{H(d, \Omega, \Lambda^k)}. \]

**Proof.** Given \( w \in H(d, \Omega, \Lambda^k) \), put \( u = dw \). Then since \( du = 0 \), applying [12, Proposition 4.1] to \( u \), we conclude that there is \( C \) independent of \( u \) and a \( v \in H^1(\Omega, \Lambda^k) \) such that
\[ u = dv, \quad \|v\|_{H^1(\Omega, \Lambda^k)}^2 \leq C \|u\|_{L^2(\Omega, \Lambda^{k+1})}^2 = C \|dw\|_{L^2(\Omega, \Lambda^{k+1})}^2. \]
Thus \( d(w - v) = 0 \). Applying [12, Proposition 4.1] again, now to \( w - v \), we find that there is a \( p \in H^1(\Omega, \Lambda^{k-1}) \) such that

\[
    w - v = dp, \quad \|p\|^2_{H^1(\Omega, \Lambda^{k-1})} \leq C\|w - v\|^2_{L^2(\Omega, \Lambda^k)} \leq 2C\|w\|^2_{H(d, \Omega, \Lambda^k)}.
\]

Thus \( w = v + dp \). Since the construction of potentials in [12] is linear, the maps \( w \mapsto v \) and \( w \mapsto p \) are linear, so the above estimates finish the proof. \( \square \)

We note that regular decompositions were established in [20, Theorem 5.2] by other means, but in their decomposition, the regular part \( S \) is not bounded by \( dw \) in general.

2.3. Interpolation into finite element spaces. Recall the well-known finite element subspaces [3, 19] of \( H(d, \Omega, \Lambda^k) \). Let \( P_r \) denote the space of polynomials in \( n \) variables of degree at most \( r \), \( P_r \Lambda^k = \{ \sum_{\alpha \in \Lambda^k} p_\alpha dx^\alpha : p_\alpha \in P_r \} \), and let \( P_r \Lambda^k \subseteq P_r \Lambda^k \), for all integers \( r \geq 1 \), be as defined in [3, §5.1.3]. Let \( \Omega_h \) denote a geometrically conforming shape-regular simplicial finite element mesh of \( \Omega \). Let \( h \) denote the maximal mesh diameter \( h = \max_{K \in \Omega_h} \text{diam}(K) \). To simplify technicalities, we assume that the mesh \( \Omega_h \) is quasiuniform, so the diameter of every element is bounded above and below by some fixed constant multiples of \( \Omega \). The standard finite element subspaces of \( H(d, \Omega, \Lambda^k) \), indexed by maximal mesh element diameter \( h \), are \( V_h^{(k)} = \{ v \in H(d, \Omega, \Lambda^k) : v|_K \in P_r \Lambda^k \} \) for all \( n \)-simplices \( K \) that are elements of the mesh \( \Omega_h \). The Lagrange finite element space \( V_h^{(0)} \) will play a special role in our discussions. We now introduce three operators that map various functions into \( V_h^{(k)} \) that will be used in the sequel.

The first operator we need is a product of Clément interpolation operators [11]. Identifying the \( n \)-fold product of \( V_h^{(0)} \) as a subspace of \( H^1(\Omega, \Lambda^k) \), we denote it by \( V_h^{(0),k} \). Then the Clément interpolant \( C_h \equiv C_h^{(k)} : L^2(\Omega, \Lambda^k) \to V_h^{(0),k} \) satisfies (see [3, Theorem 5.8] and [11, Theorem 1])

\[
    \|z - C_h^{(k)}z\|_{L^2(\Omega, \Lambda^k)} \lesssim h^s \|z\|_{H^s(\Omega, \Lambda^k)}
\]

for all \( 0 \leq s \leq r + 1 \). Here and throughout, we write \( A \lesssim B \) to indicate that the quantities \( A \) and \( B \) satisfy \( A \leq CB \) with a constant \( C \) that is independent of \( h \) (but may depend on the shape regularity of \( \Omega_h \)).

The next operator is the finite element interpolant \( \Pi_h^{(k)} \), often called the canonical interpolant. The well-known degrees of freedom of \( P_r \Lambda^k \) (see [3, Theorem 5.5] or [19]) define the canonical finite element interpolant \( \Pi_h^{(k)} \) in the usual way. Although the domain of \( \Pi_h^{(k)} \) can be shown to be contained in a general (sufficiently regular) Sobolev space, throughout this paper we will view \( \Pi_h^{(k)} \) as a bounded linear operator between these discrete spaces:

\[
    \Pi_h^{(k)} : V_h^{(0),k} \to V_h^{(k)}.
\]

Lemma 4 below provide continuity and approximation estimates for \( \Pi_h^{(k)} \) on the above domain.

Since \( \Pi_h^{(k)} \) is generally unbounded on \( H(d, \Omega, \Lambda^k) \), ideas to construct bounded projectors into \( V_h^{(k)} \) were proposed in [36] and its antecedents. Such projectors are now well-known [3] by the name “bounded cochain projectors” and we shall denote them...
by $B_h^{(k)}$. It is well-known [3, Theorem 5.9] that $B_h^{(k)} : L^2(\Omega, \mathcal{A}^k) \rightarrow V_h^{(k)}$ is a bounded projection satisfying
\begin{equation}
\| w - B_h^{(k)} w \|_{L^2(\Omega, \mathcal{A}^k)} \lesssim h^s \| w \|_{H^s(\Omega, \mathcal{A}^k)} \tag{4a}
\end{equation}
\begin{equation}
dB_h^{(k)} = B_h^{(k-1)} d \tag{4b}
\end{equation}
for all $0 \leq s \leq r + 1$.

As a final note on the notation, we will omit the superscript $(k)$ indicating the form degree from any notation when no confusion can arise. For example, just as $d$ abbreviates $d^{(k)}$, we shall use $B_h$ for $B_h^{(k)}$ when the index $k$ can be understood from context.

3. The Preconditioner

3.1. Definition. Let $\tau > 0$ and let $A \equiv A_h^{(k)} : V_h^{(k)} \rightarrow V_h^{(k)}$ denote the operator defined by
\begin{equation}
(A_h^{(k)} u, v) = \tau (u, v) + (du, dv) \tag{5}
\end{equation}
for all $u, v \in V_h^{(k)}$. Algebraic multigrid preconditioners for $A_h^{(k)}$, for any form degree $k$, can be built by generalizing the ideas in [21] and [26] as we shall see in this section.

The norm generated by $A$ is defined by $\| u \|_A = (Au, u)^{1/2}$. Given two closed subspace $V, W$ of $L^2$ and a linear operator $R : V \rightarrow W$ we use $R^t : W \rightarrow V$ to denote its Hilbert adjoint defined by $(R^t w, v) = (w, Rw)$ for all $w \in W$ and $v \in V$. Let $d_h$ denote the restriction of $d$ on $V_h^{(k)}$, i.e., $d_h : V_h^{(k)} \rightarrow V_h^{(k+1)}$. Then its adjoint $d_h^t : V_h^{(k+1)} \rightarrow V_h^{(k)}$ is calculated by the above-mentioned definition.

We define the preconditioner $B \equiv B_h^{(k)} : V_h^{(k)} \rightarrow V_h^{(k)}$ for $k \geq 1$ by induction on $k$; supposing that for $k = 0$, we are given a good preconditioner $B_0 : V_h^{(0)} \rightarrow V_h^{(0)}$, i.e., there exists a $\beta \geq 1$ (independent of $\tau$) such that
\begin{equation}
\beta^{-1} (B_0 w, w) \leq (A_0)^{-1} w, w \leq \beta (B_0 w, w) \tag{6}
\end{equation}
for all $w \in V_h^{(0)}$. This supposition is justified since there are good algebraic preconditioners [18] for the Dirichlet operator (arising from $A_0$). Then the $n_k$-fold product of $B_0$, denoted by $B_0^{(k)} : V_h^{(0), k} \rightarrow V_h^{(0), k}$, preconditions $A_0^{(k)} : V_h^{(0), k} \rightarrow V_h^{(0), k}$, the $n_k$-fold product of $A_0$. Our aim is to to use this to precondition $B_h^{(k)}$ for $k > 0$.

We need one more ingredient, the operator $D_h \equiv D_h^{(k)} : V_h^{(k)} \rightarrow V_h^{(k)}$ defined by
\begin{equation}
(D_h u, v) = (h^{-2} + \tau)(u, v) \tag{7}
\end{equation}
for all $u, v \in V_h^{(k)}$. Finally, we define the preconditioner by
\begin{equation}
B \equiv B_h^{(k)} = D_h^{-1} + \Pi_h B_0^{(k)} \Pi_h^t + \tau^{-1} d_h B_h^{(k-1)} d_h^t \tag{7}
\end{equation}
for all $1 \leq k \leq n$. Clearly, a practical implementation of this preconditioner would need implementations of $\Pi_h$, $d_h$, and $B_0^{(k)}$. The latter has been amply clarified in the literature (see e.g., [18]). In Section 4, we will provide more details on the implementation of $\Pi_h$ and $d_h$ when $n = 4$. 
Note that when the last term in (7) is recursively expanded, some simplification occurs. I.e., we have
\[ d_h B^{(k-1)} d_h^t = d_h^{(k-1)} \left[ (D_h^{(k-1)})^{-1} + \Pi_h^{(k-1)} B^{(0),k-1} (\Pi_h^{(k-1)})^t \right. \]
\[ + \tau^{-1} d_h^{(k-2)} B^{(k-2)} (d_h^{(k-2)})^t \left. (d_h^{(k-1)})^t \right] (d_h^{(k-1)})^t \]
\[ = d_h^{(k-1)} \left[ (D_h^{(k-1)})^{-1} + \Pi_h^{(k-1)} B^{(0),k-1} (\Pi_h^{(k-1)})^t \right] (d_h^{(k-1)})^t \]
(8)
because \( d_h^{(k-1)} d_h^{(k-2)} = 0 \). Thus the cost of applying the preconditioner \( B^{(k)} \) (ignoring the cost of inversion of \( D_h \) and the application of \( \Pi_h \)) is dominated by the cost of applying \( B^{(0),k-1} \) and \( B^{(0),k} \), i.e., the cost of applying \( B^{(0)} \)
\[ n_k + n_{k-1} = \left( \frac{n+1}{k} \right) \]
times. This also shows that an implementation of \( B \) using only the above-mentioned nonzero terms would be more efficient (than simply implementing (7) recursively).  

3.2. Analysis. We begin by describing a scaling argument for \( k \)-forms. Let \( \hat{K} \) denote the unit \( n \)-simplex. There is an affine homeomorphism \( \Phi_K : \hat{K} \to K \) for any \( n \)-simplex \( K \). Let \( h_K = \text{diam}(K) \). Suppose \( v \) is a \( k \)-form in \( L^2(\hat{K},\mathbb{R}^k) \). Its pullback under \( \Phi_K \) is a \( k \)-form on \( \hat{K} \) denoted by \( \Phi_K^* v \).

Lemma 2 (Scaling of pullback). For all \( v \in L^2(\hat{K},\mathbb{R}^k) \),
\[ \| \Phi_K^* v \|_{L^2(\hat{K},\mathbb{R}^k)}^2 \lesssim h_K^{2k-n} \| v \|_{L^2(K,\mathbb{R}^k)}^2 \lesssim \| \Phi_K^* v \|_{L^2(\hat{K},\mathbb{R}^k)}^2 \] 
(9)
and for all \( v \in H^1(K,\mathbb{R}^k) \),
\[ |\Phi_K^* v|_{H^1(\hat{K},\mathbb{R}^k)}^2 \lesssim h_K^{2+2k-n} \| v \|_{H^1(K,\mathbb{R}^k)}^2 \lesssim |\Phi_K^* v|_{H^1(\hat{K},\mathbb{R}^k)}^2 \] 
(10)
Proof. Let \( v = \sum_{\alpha \in I_k} v_\alpha dx^\alpha \). Its pullback \( \hat{v} = \Phi_K^* v \) when expanded in elementary form basis at any \( \hat{x} \in \hat{K} \), takes the form
\[ \hat{v}(\hat{x}) = \sum_{\alpha \in I_k} \sum_{i=1}^n v_{\alpha_1,...,\alpha_k}(\Phi_K^{-1} \hat{x}) \frac{\partial x^{\alpha_1}}{\partial \hat{x}^{i_1}} \frac{\partial x^{\alpha_2}}{\partial \hat{x}^{i_2}} \cdots \frac{\partial x^{\alpha_k}}{\partial \hat{x}^{i_k}} d\hat{x}^{i_1} \wedge d\hat{x}^{i_2} \wedge \cdots \wedge d\hat{x}^{i_k}. \]
Since each of the derivatives \( \partial x^{\alpha_i}/\partial \hat{x}^{i_i} \) are bounded by some factor of \( h_K \),
\[ \| \hat{v} \|_{L^2(\hat{K},\mathbb{R}^k)}^2 \lesssim \sum_{\alpha \in I_k} \sum_{i=1}^n \sum_{i=1}^n \left\| \sum_{\alpha_1,...,\alpha_k}(\Phi_K^{-1} \hat{x}) \frac{\partial x^{\alpha_1}}{\partial \hat{x}^{i_1}} \frac{\partial x^{\alpha_2}}{\partial \hat{x}^{i_2}} \cdots \frac{\partial x^{\alpha_k}}{\partial \hat{x}^{i_k}} \right\|^2_{L^2(\hat{K})} \]
\[ \lesssim \sum_{\alpha \in I_k} h_K^{2k} \| v_\alpha \|_{L^2(K)}^2 \lesssim h_K^{2k} \| \Phi_K^{-1} \|_{L^2(K)} \sum_{\alpha \in I_k} \| v_\alpha \|_{L^2(K)}^2 \]
\[ \lesssim h_K^{2k-n} \| v \|_{L^2(\hat{K},\mathbb{R}^k)}^2. \]
This proves one of the inequalities in (9) and the remaining bound is established by considering \( \Phi_K^{-1} \).
To prove (10), applying (1) but with norm replaced by seminorm,

\[ |\hat{\beta}|_{H^1(\hat{K},\mathbb{A}^k)}^2 = \sum_{\beta \in I_k} |\hat{\beta}|_{H^1(\hat{K},\mathbb{A}^k)}^2 \]

\[ \leq \sum_{\alpha \in I_k} \sum_{i=1}^n \cdots \sum_{i=1}^n \sum_{i=1}^n \left( \frac{\partial}{\partial x^l} \left( v_{\alpha_1,\ldots,\alpha_k} (\Phi_{K}^{-1} \hat{x}) \partial x^{\alpha_1} \partial x^{\alpha_2} \cdots \partial x^{\alpha_k} \right) \right)^2 L^2(\hat{K}) \]

\[ = \sum_{\alpha \in I_k} \sum_{i=1}^n \cdots \sum_{i=1}^n \sum_{i=1}^n \sum_{i=1}^n \left( \frac{\partial x^m}{\partial x^l} \partial_m v_{\alpha_1,\ldots,\alpha_k} \frac{\partial x^{\alpha_1}}{\partial x^{i_1}} \frac{\partial x^{\alpha_2}}{\partial x^{i_2}} \cdots \frac{\partial x^{\alpha_k}}{\partial x^{i_k}} \right)^2 \frac{|\hat{K}|}{|K|} \]

\[ \leq h_{K}^{2+2k} \frac{|\hat{K}|}{|K|} \sum_{\alpha \in I_k} \sum_{i=1}^n \left( \partial_m v_{\alpha} \right)^2 \]

\[ \leq h_{K}^{2+2k-n} |v|^2_{H^1(\hat{K},\mathbb{A}^k)}. \]

The reverse inequality is proved similarly. \qed

**Lemma 3** (Inverse inequality). For all \( v_h \in V_h^{(k)} \),

\[ \|dv_h\| \preceq h^{-1} \|v_h\| \]

**Proof.** Since \( v_h \) is a \( k \)-form, it can be expressed in the basis expansion

\[ v_h(x) = \sum_{\alpha \in I_k} v_{\alpha}(x) dx^\alpha. \]

Thus (2) and the triangle inequality implies

\[ \|dv_h\|^2 \preceq \sum_{\alpha \in I_k} \sum_{i=1}^n \left( \partial_i v_{\alpha} \right)^2. \quad (11) \]

On any \( n \)-simplex \( K \in \Omega_h \), the restriction \( v_{\alpha}|_K \) is a polynomial of degree at most \( r \), so the standard inverse inequality for polynomials yields, with \( h_K = \text{diam}(K) \),

\[ \|\partial_i v_{\alpha}\|^2_{L^2(K,\mathbb{F})} \preceq h_K^{-2} \|v_{\alpha}\|^2_{L^2(K,\mathbb{F})} \]

which when summed over all \( K \in \Omega_h \) and applied in (11), proves the lemma. \qed

**Lemma 4** (Canonical interpolant). For all \( v_h \in V_{h}^{(0),k} \)

\[ \|\Pi_h v_h\| \preceq \|v_h\| \quad (12) \]

\[ \|\Pi_h v_h - v_h\| \preceq h \|v_h\|_{H^1(\Omega,\mathbb{A}^k)} \quad (13) \]

\[ \|d\Pi_h v_h\| \preceq \|v_h\|_{H^1(\Omega,\mathbb{A}^k)}. \quad (14) \]

**Proof.** Let \( \Pi_K : P_r \mathbb{A}^k(K) \to P_r^- \mathbb{A}^k(K) \) be the canonical interpolant on \( K \), i.e., \( \Pi_K = (\Pi_h v)|_K \) for any \( v \in V_r^{(0),k} \). Recall that any \( v \) in \( V_h^{(0),k} \subset H^1(\Omega,\mathbb{A}^k) \), when restricted to \( K \), lies in \( P_r \mathbb{A}^k \). It is easy to check for any \( v \in P_r \mathbb{A}^k \)

\[ \Phi_K^* \Pi_K v = \Pi_K \Phi_K^* v. \quad (15) \]
Since $\Pi_{h}^{k} : P_{r,h}^{k} \to P_{r,h}^{k}(\hat{K})$ is a linear map between finite dimensional spaces, it is bounded. Using Lemma 2, we have
\[
\|\Pi_{h} v\|_{L^{2}(K,h^{k})}^{2} \lesssim h^{n-2k} \|\Pi_{h}^{*} v\|_{L^{2}(K,h^{k})}^{2} = h^{n-2k} \|\Pi_{K}^{*} v\|_{L^{2}(K,h^{k})}^{2} \\
\lesssim h^{n-2k} \|\Phi_{K}^{*} v\|_{L^{2}(K,h^{k})}^{2} \lesssim h^{n-2k} h^{2k-n} \|v\|_{L^{2}(K,h^{k})}^{2}.
\]
When summed over all $K \in \Omega_{h}$, this proves (12).

To prove (13), we note that $c - \Pi_{h}^{k} c = 0$ for any constant function $c$. Hence choosing $c$ to be the mean value of $\Phi_{K}^{*} v$ on $\hat{K}$,
\[
\|\Pi_{h} v - v\|_{L^{2}(K,h^{k})}^{2} \lesssim h^{n-2k} \|(\Pi_{h} - I)(\Phi_{K}^{*} v - c)\|_{L^{2}(K,h^{k})}^{2} \\
\lesssim h^{n-2k} \|\Phi_{K}^{*} v - c\|_{L^{2}(K,h^{k})}^{2} \lesssim h^{n-2k} \|\Phi_{K}^{*} v\|_{H^{1}(K,h^{k})}^{2} \\
\lesssim h^{n-2k} h^{2k-n} \|v\|_{H^{1}(K,h^{k})}^{2},
\]
where we have again used Lemma 2. Summing over all elements, this proves (13).

Finally to prove (14), we note that the canonical interpolant commutes with the exterior derivative when applied to smooth functions. In particular, on any $v \in P_{r,h}^{k}(K)$, we have $d\Pi_{h}^{(k)} v|_{K} = \Pi_{h}^{(k+1)} dv|_{K}$. Hence, using the already established (12),
\[
\|d\Pi_{h} v\|_{L^{2}(K,h^{k})}^{2} \lesssim \|dv\|_{L^{2}(K,h^{k})}^{2} \lesssim \|v\|_{H^{1}(K,h^{k})}^{2}.
\]
Summing over all elements, this proves (14). \hfill \Box

**Lemma 5** (Stable decomposition). For any $u_{h} \in V_{h}^{(k)}$, there are functions $s_{h} \in V_{h}^{(k)}$, $z_{h} \in V_{h}^{(0),k}$, and $p_{h} \in V_{h}^{(k-1)}$ such that
\[
\tag{16}
u_{h} = s_{h} + \Pi_{h} z_{h} + dp_{h}
\]
and
\[
(\tau^{2} + \tau^{2})|s_{h}|^{2} + \tau|p_{h}|^{2} + \tau|dp_{h}|^{2} \\
+ \tau|z_{h}|^{2} + |z_{h}|_{H^{1}(\Omega,h^{k})}^{2} \lesssim \tau|u_{h}|^{2} + (1 + \tau)|du_{h}|^{2}.
\]
\[
\tag{17}
Proof. We apply Theorem 1 to $u_{h} \in V_{h}^{(k)} \subset H(d,\Omega,h^{k})$ to obtain
\[
\tag{18}
u_{h} = z + dp,
\]
\[
\tag{19}
|z|_{H^{1}(\Omega,h^{k})} \leq C_{1} |du_{h}|, \quad |p|_{H^{1}(\Omega,h^{k-1})} \leq C_{1} |u_{h}|_{H(d,\Omega,h^{k})},
\]
where $z = Su$ and $p = Pu$. Now let $z_{h} = C_{h} z \in V_{h}^{(0),k}$ denote the Clement interpolant of $z$. Applying $B_{h}^{(k)}$ to both sides of (18) and using (4),
\[
u_{h} = B_{h} z + dB_{h} p.
\]
Then (16) follows with
\[
s_{h} = B_{h} z - \Pi_{h} z_{h}, \quad p_{h} = B_{h} p
\]
and it only remains to prove the estimate (17).
Observe that
\[
\|z_h\|_{A(0)}^2 = \tau \|z_h\|^2 + \|d^h z_h\|^2 < \tau \|z\|^2 + |z|^2_{H^1(\Omega, \mathbb{R}^k)} \quad \text{by (3)}
\]
\[
\tau \|p_h\|^2 = \tau \|B_h p\|^2 \leq \tau \|p\|^2 \quad \text{by (4)}
\]
\[
\|d p_h\|^2 = \|d B_h p\|^2 = \|B_h dp\|^2 < \|dp\|^2 \quad \text{by (4)}
\]
\[
\|s_h\|^2 \leq (\|B_h^{(k)} z - z\| + \|z - z_h\| + \|z_h - \Pi_h^{(k)} z_h\|)^2
\]
\[
< h^2 \|z\|^2_{H^1(\Omega, \mathbb{R}^k)} < h^2 \|du_h\|^2 \quad \text{by (4), (3) and (13)}.
\]

Inequality (17) follows by combining these estimates. □

With the above lemmas, we are ready to conclude the analysis. The basis for the analysis of auxiliary space preconditioners is the standard “fictitious space lemma” (see e.g., [21, 32, 44]) which we state without proof below in a form convenient for us. Suppose we want to precondition a self-adjoint positive definite operator \(A\) on a finite-dimensional Hilbert space \(V\) using

1. a self-adjoint positive definite operator \(S: V \to V\) whose inverse is easy to apply,  
2. two “auxiliary” Hilbert spaces \(\tilde{V}_1\) and \(\tilde{V}_2\) and linear operators \(\tilde{R}_i: \tilde{V}_i \to V\), and  
3. two further self-adjoint positive definite operators \(\tilde{A}_i: \tilde{V}_i \to \tilde{V}_i\) on the auxiliary spaces whose inverses are easy to apply.

In this setting, the following result guides the preconditioner design.

**Lemma 6** (Nepomnyaschikh lemma). Suppose there are positive constants \(c_1, c_2, c_s > 0\) such that for all \(\tilde{v}_j \in \tilde{V}_j\), \(j = 1, 2\), and \(v \in V\),

\[
\|\tilde{R}_1 \tilde{v}_1\|_A \leq c_1 \|\tilde{v}\|_{\tilde{A}_1}, \quad \|\tilde{R}_2 \tilde{v}_2\|_A \leq c_2 \|\tilde{v}\|_{\tilde{A}_2}, \quad \|v\|_A \leq c_s \|v\|_S. \quad (20)
\]

Suppose also that given any \(v \in V\) there are \(s \in V\), \(\tilde{v}_i \in \tilde{V}_i\) such that \(s + \tilde{R}_1 \tilde{v}_1 + \tilde{R}_2 \tilde{v}_2 = v\) and

\[
\|s\|^2_S + \|\tilde{v}_1\|^2_{\tilde{A}_1} + \|\tilde{v}_2\|^2_{\tilde{A}_2} \leq c_0^2 \|v\|^2_A. \quad (21)
\]

Then \(P = S^{-1} + \tilde{R}_1 \tilde{A}_1^{-1} \tilde{R}_1 + \tilde{R}_2 \tilde{A}_2^{-1} \tilde{R}_2\) preconditions \(A\) and the spectrum of \(PA\) is contained in the interval \([c_0^2, c_1^2 + c_s^2 + c_2^2]\).

**Theorem 7.** Let \(0 < \tau \leq 1\) and let \(A\) and \(B\) be defined by (5) and (7), respectively. Suppose (6) holds. Then for each \(1 \leq k \leq n - 1\), there is an \(\alpha \geq 1\) independent of \(h\) and \(\tau\) such that spectral condition number of \(BA\) satisfies

\[
\kappa(BA) \leq \alpha^2 \beta^2.
\]

**Proof.** First, we analyze the preconditioner

\[
P^{(k)} = D_h^{-1} + \Pi_h (A^{(0),k})^{-1} \Pi_h + \tau^{-1} d_h (A^{(k-1)})^{-1} d_h. \quad (22)
\]
For this, we apply Lemma 6 with

\[
\begin{align*}
V &= V_h^{(k)}, & A &= A^{(k)}, & S &= D_h, \\
\tilde{V}_1 &= V_h^{(0),k}, & \tilde{A}_1 &= A^{(0),k}, & \tilde{R}_1 &= \Pi_h^{(k)}, \\
\tilde{V}_2 &= V_h^{(k-1)}, & \tilde{A}_2 &= \tau A^{(k-1)}, & \tilde{R}_2 &= d_h^{(k-1)}.
\end{align*}
\]

We must verify the conditions (20) and (21) of the lemma.

To verify (20), we use the following bounds, which hold for any \( z_h \in \tilde{V}_1, p_h \in \tilde{V}_2, \) and \( v_h \in V): \]

\[
\left\| \tilde{R}_1 z_h \right\|_A^2 = \| \Pi_h z_h \|_A^2 = \tau \| \Pi_h z_h \|_2^2 + \| d \Pi_h z_h \|_2^2 \\
\lesssim \tau \| z_h \|_2^2 + \| z_h \|_{H^1(\Omega, A^k)} = \| z_h \|_{\tilde{A}_1},
\]

(23)

\[
\left\| \tilde{R}_2 p_h \right\|_A^2 = \| d p_h \|_A^2 = \tau \| d p_h \|_2^2 \leq \tau \left( \| d p_h \|_2^2 + \| p_h \|_2^2 \right) \\
\leq \tau \| p_h \|_A^2 = \| p_h \|_{\tilde{A}_2},
\]

\[
\left\| v_h \right\|_A^2 = \tau \| v_h \|_2^2 + \| d v_h \|_2^2 \\
\lesssim (h^{-2} + \tau) \| v_h \|_2^2 = \| v_h \|_{D_h}^2.
\]

(24)

We have used the inverse inequality of Lemma 3 in the last bound. With the above bounds, we have verified (20).

Next, to verify (21), we use Lemma 5 to decompose any \( u_h \) in \( V \) into \( u_h = s_h + \tilde{R}_1 z_h + \tilde{R}_2 p_h = s_h + \Pi_h z_h + d p_h \) and apply (17). Since \( \tau \leq 1, \) (17) implies

\[
\left\| s_h \right\|_{D_h}^2 + \left\| p_h \right\|_{\tilde{A}_2}^2 + \left\| z_h \right\|_{\tilde{A}_1}^2 = \left\| s_h \right\|_{D_h}^2 + \tau \left\| p_h \right\|_{A}^2 + \left\| z_h \right\|_{\tilde{A}_1}^2 \\
\leq \left\| s_h \right\|_{D_h}^2 + \tau \left( \| p_h \|_2^2 + \| d p_h \|_2^2 \right) + \left\| z_h \right\|_{\tilde{A}_1}^2 \\
\lesssim \tau \left\| u_h \right\|_2^2 + (1 + \tau) \| d u_h \|_2^2 \\
\lesssim \| u_h \|_{A}^2.
\]

This verifies (21). Thus Lemma 6 yields the existence of an \( \alpha_k \geq 1 \) (after overestimating the constants if necessary) such that

\[
\frac{1}{\alpha_k} (P^{(k)} v, v) \leq ((A^{(k)})^{-1} v, v) \leq \alpha_k (P^{(k)} v, v)
\]

(25)

for all \( v \in V \).

To complete the proof, we use the quadratic form of \( P^{(k)} \) to estimate that of \( B \). For any \( v \in V \),

\[
(B^{(k)} v, v) = (D_h^{-1} v, v) + (B^{(0),k} \Pi_h v, \Pi_h v) + \tau^{-1} (d_h B^{(k-1)} d_h^t v, v) \\
= ((D_h^{(k)})^{-1} v, v) + (B^{(0),k} \Pi_h v, \Pi_h v) \\
+ \tau^{-1} \left[ ((D_h^{(k-1)})^{-1} d_h^t v, d_h^t v) + ((B^{(0),k-1})^{-1} \Pi_h d_h^t, \Pi_h d_h^t) \right]
\]
where we have used (8). Now, using (6) and (22), and (31),
\[
(B^{(k)}v, v) \leq (D_h^{-1}v, v) + \beta((A^{(0),k})^{-1}\Pi_{h}v, \Pi_{h}v)
\]
\[
+ \tau^{-1} \left[ (D_h^{(k-1)})^{-1}d_h^{(k-1)}v, d_h^{(k-1)}v \right] + \beta((A^{(0),k-1})^{-1}\Pi_{h}d_h^{(k-1)}v, \Pi_{h}d_h^{(k-1)}v)
\]
\[
\leq \beta \left[(D_h^{-1}v, v) + ((A^{(0),k})^{-1}\Pi_{h}v, \Pi_{h}v) + \tau^{-1}(P^{(k-1)}d_h^{(k-1)}v, d_h^{(k-1)}v)\right]
\]
\[
\leq \beta \left[(D_h^{-1}v, v) + ((A^{(0),k})^{-1}\Pi_{h}v, \Pi_{h}v) + \tau^{-1}\alpha_{k-1}((A^{(k-1)})^{-1}d_h^{(k-1)}v, d_h^{(k-1)}v)\right]
\]
\[
\leq \beta\alpha_{k-1}(P^{(k)}v, v) \leq \beta\alpha_{k-1}\alpha_{k}((A^{(k)})^{-1}v, v).
\]
Combining with a similarly provable lower inequality, we have
\[
\beta^{-1}\alpha_{k-1}\alpha_{k}^{-1}(B^{(k)}v, v) \leq ((A^{(k)})^{-1}v, v) \leq \beta\alpha_{k-1}\alpha_{k}(B^{(k)}v, v)
\]
for all \(v \in V_h^{(k)}\). \(\square\)

3.3. A variant. The preconditioner in (7) is a generalization of auxiliary space preconditioner in the form given in [21]. An auxiliary space preconditioner in a slightly different form was proposed in [26, 27]. It can also be extended to higher dimensions as we now show. To define this variant, let \(Q_0\) denote the projection satisfying
\[
Q_0u \in dV_h^{((k-1))}: \quad (Q_0u, \kappa) = (u, \kappa) \quad \text{for all } \kappa \in dV_h^{((k-1))}.
\]
Then \(A_0 = Q_0A\big|_{dV_h} : dV_h^{((k-1))} \rightarrow dV_h^{((k-1))}\) satisfies
\[
(A_0\kappa_1, \kappa_2) = (A\kappa_1, \kappa_2) = \tau(\kappa_1, \kappa_2) \quad (26)
\]
for all \(\kappa_1, \kappa_2 \in dV_h^{((k-1))}\) because \(d \circ d = 0\). Clearly \(A_0\) is invertible for all \(\tau > 0\). Let \(B_0 : dV_h^{((k-1))} \rightarrow dV_h^{((k-1))}\) be a preconditioner for \(A_0\), i.e., there is a \(\beta_0 \geq 1\) such that
\[
\beta_0^{-1}(B_0\kappa, \kappa) \leq (A_0^{-1}\kappa, \kappa) \leq \beta_0(B_0\kappa, \kappa) \quad (27)
\]
for all \(\kappa\) in \(dV_h^{((k-1))}\). Using \(B_0\), we define our second auxiliary space preconditioner \(C : V_h^{(k)} \rightarrow V_h^{(k)}\) by
\[
C = D_h^{-1} + \Pi_hB^{(0),k}\Pi_h + B_0Q_0 \quad (28)
\]
Unlike (7), some care is needed to design and implement \(B_0\). Consider, for instance, the case \(B_0 = A_0^{-1}\). Although it appears from (26) that \(A_0^{-1}\) is simply the inverse of a mass matrix scaled by \(\tau^{-1}\), the difficulty is that we usually do not have a basis for \(dV_h^{((k-1))}\) in a typical implementation. To compute the action of the last term in (28) on some \(v \in V_h^{(k)}\), namely \(\kappa_1 = A_0^{-1}Q_0v\), we write \(A_0\kappa_1 = Q_0v\) and apply (26) to observe that \(\kappa_1\) solves
\[
\tau(\kappa_1, \kappa_2) = (v, \kappa_2) \quad \text{for all } \kappa_2 \in dV_h^{((k-1))}.
\]
Since we do not have a basis for \(dV_h^{((k-1))}\), we use potentials \(p_1, p_2\) in \(V_h^{((k-1))}\) (for which we do have a basis) to express \(\kappa_i = dp_i\). Then (29) implies that \(p_1\) in \(V_h^{((k-1))}\) solves
\[
\tau(dp_1, dp_2) = (v, dp_2) \quad \text{for all } p_2 \in V_h^{((k-1))}.
\]
Even if these equations do not uniquely determine \(p_1\), this approach does lead to a practical algorithm because we only need \(dp_1\) to apply (28). Note that \(p_1\) is determined only up to the kernel of \(d\), but \(\kappa_1 = dp_1\) is uniquely determined. One strategy to compute \(dp_1\) is to apply \(d\) after computing a solution \(p_1\) given by the pseudoinverse of
the system in (30). Another is to use an iterative technique that converges to one solution of (30). One may also use a combination of such strategies, such as a multilevel iteration with smoothers that are convergent despite the singularity in (30), combined with a coarse-level solver obtained from a pseudoinverse. For more details, the reader may consult [26, 27] or the implementations in [22, 30]. Notwithstanding the complications in implementation, the analysis is a straightforward application of the previous results.

**Theorem 8.** Let $0 < \tau \leq 1$ and let $A$ and $C$ be defined by (5) and (28), respectively. Suppose (6) and (27) holds and let $\beta_1 = \max(\beta, \beta_0)$. Then for each $1 \leq k \leq n - 1$, there is an $\alpha \geq 1$ independent of $h$ and $\tau$ such that spectral condition number of $CA$ satisfies

$$\kappa(CA) \leq \alpha^2 \beta_1^2.$$ 

**Proof.** As in the proof of Theorem 7, we consider an intermediate $P = D_h^{-1} + \Pi_h(A^{(0), k})^{-1} \Pi_h^1 + A_0^{-1}Q_0$, which is the preconditioner of Lemma 6 with

$$V = V_h^{(k)}, \quad A = A^{(k)}, \quad S = D_h,$$
$$\tilde{V}_1 = V_h^{(0), k}, \quad \tilde{A}_1 = A^{(0), k}, \quad \tilde{R}_1 = \Pi_h^{(k)},$$
$$\tilde{V}_2 = dV_h^{(k-1)}, \quad \tilde{A}_2 = A_0 = \tau I, \quad \tilde{R}_2 = I.$$

We proceed to verify the conditions (20) and (21). The following estimates holds for all $z_h \in \tilde{V}_1$, $\kappa_h \in \tilde{V}_2$, and $v_h \in V$:

$$\|\tilde{R}_1 z_h\|^2_A < \|z_h\|^2_{A_1},$$
by (23),

$$\|\tilde{R}_2 \kappa_h\|^2_A = \|\kappa_h\|^2_A = \tau \|\kappa_h\|^2 = \|\kappa_h\|^2_{A_2},$$

$$\|v_h\|^2_A < \|v_h\|^2_{D_h},$$
by (24).

Hence we have verified (20). To verify (21), as before, we use Lemma 5 to decompose any $u_h$ in $V$ into $u_h = s_h + \tilde{R}_1 z_h + \tilde{R}_2 \kappa_h = s_h + \Pi_h z_h + \kappa_h$, where $\kappa_h = dp_h \in \tilde{V}_2$, and apply (17) to get

$$\|s_h\|^2_{D_h} + \tau \|\kappa_h\|^2 + \|z_h\|^2_{A_1} < \|u_h\|^2_A,$$

where we have used the assumption that $\tau$ is bounded. This verifies (21). Thus Lemma 6 yields the existence of an $\alpha_k \geq 1$ (after overestimating the constants if necessary) such that

$$\alpha_k^{-1}(Pv, v) \leq (A^{-1}v, v) \leq \alpha_k(Pv, v)$$

for all $v \in V$.

To complete the proof, observe that for any $v \in V$,

$$(Cv, v) = (D_h^{-1}v, v) + (B^{(0), k} \Pi_h v, \Pi_h v) + (B_0 Q_0 v, Q_0 v)$$

$$\leq (D_h^{-1}v, v) + \beta((A^{(0), k})^{-1} \Pi_h v, \Pi_h v) + \beta_0(A_0^{-1}Q_0 v, Q_0 v)$$

$$\leq \beta_1(Pv, v) \leq \beta_1 \alpha_k(A^{-1}v, v).$$

Together with a similarly provable other-side bound, we have $\beta_1^{-1} \alpha_k^{-1}(Cv, v) \leq (A^{-1}v, v) \leq \beta_1 \alpha_k(Cv, v)$ for all $v \in V$. \qed
4. Implementation in 4 dimensions

In this section, we detail the implementation of the building blocks of the preconditioner in four dimensions. These details form the basis for our publicly available implementation of the preconditioner in the MFEM package [30]. The vector space $\Lambda^k$ in general dimensions is not usually implemented in finite element packages (yet). Therefore, our approach is to view forms using elements (called “proxies” below) of the more standard vector spaces like $\mathbb{R}$, $\mathbb{R}^4$, and the vector space of $4 \times 4$ skew symmetric matrices $\mathbb{K}$.

4.1. Proxies of forms. As already mentioned in §2.1, any $\varphi \in \Lambda^k$ has the basis expansion

$$\varphi = \sum_{1 \leq i_1 < \cdots < i_k \leq 4} \varphi_{i_1 \cdots i_k} dx^{i_1} \wedge \cdots \wedge dx^{i_k}.$$  \hspace{1cm} (32)

Here the sum runs over all indices in $I_k$ with four components. The numbers $\varphi_{i_1 \cdots i_k}$, called the “components” or the “coefficients” of the form, are arranged into vectors or matrices that form “proxies” of $k$-forms, as defined below.

The proxy of a $k$-form $\varphi$ is denoted by $[\varphi]^{(k)}$ and is defined as follows. In the case of a 0-form $\varphi$, we set $[\varphi]^{(0)} = \varphi$. In the case of higher form degrees, we use the components of $\varphi$ in (32), namely $\varphi_i$ for 1-form, $\varphi_{ij}$ for 2-form, and $\varphi_{ijk}$ for 3-form, to define proxies:

$$[\varphi]^{(1)} = \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \end{bmatrix}, \quad [\varphi]^{(2)} = \begin{bmatrix} 0 & \varphi_{34} & -\varphi_{24} & \varphi_{23} \\ -\varphi_{34} & 0 & \varphi_{14} & -\varphi_{13} \\ \varphi_{24} & -\varphi_{14} & 0 & \varphi_{12} \\ -\varphi_{23} & \varphi_{13} & -\varphi_{12} & 0 \end{bmatrix}, \quad [\varphi]^{(3)} = \begin{bmatrix} \varphi_{234} \\ -\varphi_{134} \\ \varphi_{124} \\ -\varphi_{123} \end{bmatrix}.$$  \hspace{1cm} (33)

Finally a $\varphi \in \Lambda^4$ has only one component $\varphi_{1234}$, so we set $[\varphi]^{(4)} = \varphi_{1234}$. Thus $[\varphi]^{(k)}$ introduces a one-to-one onto correspondence from $\Lambda^k$ to $\mathbb{R}, \mathbb{R}^4, \mathbb{K}, \mathbb{R}^4$, and $\mathbb{R}$, for $k = 0, 1, 2, 3, 4$, respectively.

Some identities are expressed better using the permutation (or the Levi-Civita) symbol $\varepsilon_{i_1 i_2 \cdots i_n}$, whose definition we recall briefly. For any $n$ and any indices $i_k$ in $\{1, 2, \ldots, n\}$, the value of $\varepsilon_{i_1 i_2 \cdots i_n}$ is zero when any two indices are equal. When the indices are distinct, $i_1 i_2 \cdots i_n$ is a permutation of $1, 2, \ldots, n$ and the value of $\varepsilon_{i_1 i_2 \cdots i_n}$ is set to the sign of the permutation. It can be easily verified that the $(i,j)$th entry of the above-defined skew symmetric matrix proxy of a $\varphi \in \Lambda^2$ and the $i$th component of the proxy vector of a $\varphi \in \Lambda^3$ are given by

$$[\varphi]^{(2)}_{ij} = \sum_{1 \leq k < l \leq 4} \varepsilon_{ijkl} \varphi_{kl}, \quad [\varphi]^{(3)}_i = \sum_{1 \leq j < k < l \leq 3} \varepsilon_{ijkl} \varphi_{jkl},$$  \hspace{1cm} (33)

where the sums run over increasing multi-indices in $I_2$ and $I_3$, respectively.

Next, we define two cross products (both denoted by $\times$) in the four-dimensional case. Recall that for any $u, v \in \mathbb{R}^3$, the $i$th component of the standard cross product $u \times v$ is given by $[u \times v]_i = \sum_{j,k=1}^3 \varepsilon_{ijk} u_j v_k$. Analogously, we define

$$[u \times v]_{ij} = \sum_{k,l=1}^4 \varepsilon_{ijkl} u_k v_l, \quad u, v \in \mathbb{R}^4,$$
i.e., this cross product of two 4-dimensional vectors yields a skew-symmetric matrix. We also define the cross product of two skew symmetric matrices \( \kappa, \eta \) in \( \mathbb{K} \) by
\[
\kappa \times \eta = \sum_{1 \leq i < j \leq 4} \sum_{1 \leq k < l \leq 4} \varepsilon_{ijkl} \kappa_{ij} \eta_{kl}, \quad \kappa, \eta \in \mathbb{K},
\]
i.e., result of the cross product of two matrices in \( \mathbb{K} \) produces a real number by a formula analogous to the cross product of two-dimensional vectors (and the analogy is clear once we view the skew-symmetric matrices as vectors in \( \mathbb{R}^6 \)).

These operations, together with other standard multiplication operations yield (after some elementary, albeit tedious calculations) formulas for the wedge product and form action in terms of proxies, as summarized in the next result. The standard products used below include the scalar multiplication, the inner product of two vectors in \( \mathbb{R}^4 \) (denoted by \( \cdot \)), the matrix-vector product of elements in \( \mathbb{K} \) with \( \mathbb{R}^4 \), and the Frobenius inner product between matrices (denoted by :).

**Proposition 9.** The following identities hold for the wedge product:
\[
[\eta \wedge \varphi]^{(k)} = [\varphi \wedge \eta]^{(k)} = [\varphi]^{(0)}[\eta]^{(k)}, \quad \varphi \in \Lambda^0, \eta \in \Lambda^k, \quad k = 0, \ldots, 4, \quad (34a)
\]
\[
-[\eta \wedge \varphi]^{(2)} = [\varphi \wedge \eta]^{(2)} = [\varphi]^{(1)} \times [\eta]^{(1)}, \quad \varphi \in \Lambda^1, \eta \in \Lambda^1, \quad (34b)
\]
\[
[\eta \wedge \varphi]^{(3)} = [\varphi \wedge \eta]^{(3)} = [\eta]^{(2)} [\varphi]^{(1)}, \quad \varphi \in \Lambda^1, \eta \in \Lambda^2, \quad (34c)
\]
\[
-[\eta \wedge \varphi]^{(4)} = [\varphi \wedge \eta]^{(4)} = [\varphi]^{(1)} \cdot [\eta]^{(3)}, \quad \varphi \in \Lambda^1, \eta \in \Lambda^3, \quad (34d)
\]
\[
[\eta \wedge \varphi]^{(4)} = [\varphi \wedge \eta]^{(4)} = [\varphi]^{(2)} \times [\eta]^{(2)}, \quad \varphi \in \Lambda^2, \eta \in \Lambda^2. \quad (34e)
\]

The values of forms applied to vectors \( u, v, w, z \in \mathbb{R}^4 \) are given by
\[
\varphi(v) = [\varphi]^{(1)} \cdot v, \quad \varphi \in \Lambda^1, \quad (35a)
\]
\[
\varphi(u, v) = [\varphi]^{(2)} : (u \times v), \quad \varphi \in \Lambda^2, \quad (35b)
\]
\[
\varphi(u, v, w) = \det [ [\varphi]^{(3)}, u, v, w ], \quad \varphi \in \Lambda^3, \quad (35c)
\]
\[
\varphi(u, v, w, z) = [\varphi]^{(4)} \det[u, v, w, z], \quad \varphi \in \Lambda^4. \quad (35d)
\]

4.2. **The four derivatives.** Analogous to the three fundamental first order differential operators (\( \text{grad, curl, div} \)) in three dimensions, there are four first order differential operators in four dimensions, which we denote by
\[
\text{grad, Curl, Div, div}. \quad (36)
\]
The first and the last operators in (36) are standard: For any \( u \in \mathcal{D}'(\Omega, \mathbb{R}) \) define \( \text{grad} u \in \mathcal{D}'(\Omega, \mathbb{R}^4) \) as the vector whose \( i \)th component is \( \partial_i u \). For any \( v \in \mathcal{D}'(\Omega, \mathbb{R}^4) \), we set \( \text{div} v = \sum_{i=1}^4 \partial_i v_i \).

Next, we define the four-dimensional Curl in a way that brings out the analogies with the three-dimensional case. Recall that the \( i \)th component of the curl of a vector function \( w \) in three dimensions can be expressed as \( [\text{curl} \, w]_i = \sum_{j,k=1}^3 \varepsilon_{ijk} \partial_j w_k \). Analogously, for any \( w \in \mathcal{D}'(\Omega, \mathbb{R}^4) \), we define \( \text{Curl} \, w \) as the matrix in \( \mathbb{K} \) whose \((i, j)\)th entry is defined by
\[
[C\text{url} \, w]_{ij} = \sum_{k,l=1}^4 \varepsilon_{ijkl} \partial_k w_l \quad (37)
\]
i.e.,
\[
\text{Curl } w = \begin{bmatrix}
0 & \partial_3 w_4 - \partial_4 w_3 & \partial_4 w_2 - \partial_2 w_4 & \partial_2 w_3 - \partial_3 w_2 \\
\partial_4 w_3 - \partial_3 w_4 & 0 & \partial_1 w_4 - \partial_4 w_1 & \partial_4 v_1 - \partial_1 v_3 \\
\partial_1 v_4 - \partial_4 v_2 & \partial_1 v_1 - \partial_4 v_4 & 0 & \partial_1 v_2 - \partial_2 v_1 \\
\partial_3 v_2 - \partial_2 v_3 & \partial_1 v_3 - \partial_3 v_1 & \partial_2 v_1 - \partial_1 v_2 & 0
\end{bmatrix}.
\]

Finally, the remaining operation Div acts on \(\kappa \in \mathcal{D}'(\Omega, \mathbb{K})\) and produces \(\text{Div } \kappa \in \mathbb{R}^4\) by taking divergence row-wise, i.e.,
\[
[\text{Div } \kappa]_i = \sum_{j=1}^{4} \partial_j \kappa_{ij}.
\]

Note that the identities \(\text{Curl}(\text{grad } u) = 0\), \(\text{Div}(\text{Curl } w) = 0\), and \(\text{div}(\text{Div } \kappa) = 0\) follow immediately from the above definitions.

By connecting the inputs and outputs of the above-introduced four differential operators to proxies of forms, we may understand them as manifestations of exterior derivatives. In fact, the following diagram commutes:
\[
\begin{align*}
\mathcal{D}'(\Omega, \mathbb{A}^0) & \xrightarrow{d^{(0)}} \mathcal{D}'(\Omega, \mathbb{A}^1) \xrightarrow{d^{(1)}} \mathcal{D}'(\Omega, \mathbb{A}^2) \xrightarrow{d^{(2)}} \mathcal{D}'(\Omega, \mathbb{A}^3) \xrightarrow{d^{(3)}} \mathcal{D}'(\Omega, \mathbb{A}^4) \\
\mathcal{D}'(\Omega, \mathbb{R}) & \xrightarrow{\text{grad}} \mathcal{D}'(\Omega, \mathbb{R}^4) \xrightarrow{\text{Curl}} \mathcal{D}'(\Omega, \mathbb{K}) \xrightarrow{\text{Div}} \mathcal{D}'(\Omega, \mathbb{R}^4) \xrightarrow{\text{div}} \mathcal{D}'(\Omega, \mathbb{R}).
\end{align*}
\]

This follows from the identities collected next, which can again be proved by elementary calculations.

**Proposition 10.** The following identities hold:
\[
\begin{align*}
[d^{(0)} \varphi]^{(1)} &= \text{grad}([\varphi]^{(0)}), & \varphi \in \mathcal{D}'(\Omega, \mathbb{A}^0), \\
[d^{(1)} \varphi]^{(2)} &= \text{Curl}([\varphi]^{(1)}), & \varphi \in \mathcal{D}'(\Omega, \mathbb{A}^1), \\
[d^{(2)} \varphi]^{(3)} &= \text{Div}([\varphi]^{(2)}), & \varphi \in \mathcal{D}'(\Omega, \mathbb{A}^2), \\
[d^{(3)} \varphi]^{(4)} &= \text{div}([\varphi]^{(3)}), & \varphi \in \mathcal{D}'(\Omega, \mathbb{A}^3).
\end{align*}
\]

In addition to the operator Curl, another curl operator deserves mention because it fits in an alternate sequence of spaces in four dimensions. Let \(\mathbb{M}\) denote the space of \(4 \times 4\) matrices and let \(\text{skw} m = (m - m^t)/2\) for any \(m \in \mathbb{M}\). Define the curl of a skew-symmetric matrix, namely \(\text{curl} : \mathcal{D}'(\Omega, \mathbb{K}) \to \mathcal{D}'(\Omega, \mathbb{R}^4)\), and an antisymmetrization operator \(K : \mathbb{M} \to \mathbb{K}\), by
\[
[\text{curl } \omega]_i = \sum_{k,l=1}^{4} \epsilon_{ijkl} \partial_j \omega_{kl}, \quad [Km]_{ij} = \sum_{k,l=1}^{4} \epsilon_{ijkl} m_{kl}
\]
for any \(\omega \in \mathcal{D}'(\Omega, \mathbb{K})\) and \(m \in \mathbb{M}\). Also let the gradient of a vector field, \(\text{Grad} : \mathcal{D}'(\Omega, \mathbb{R}^4) \to \mathcal{D}'(\Omega, \mathbb{M})\), be defined by \([\text{Grad } u]_{ij} = \partial_j u_i\). Now, analogous to the previously discussed sequence,
\[
\begin{align*}
\mathcal{D}'(\Omega, \mathbb{R}) & \xrightarrow{\text{grad}} \mathcal{D}'(\Omega, \mathbb{R}^4) \xrightarrow{\text{Curl}} \mathcal{D}'(\Omega, \mathbb{K}) \xrightarrow{\text{Div}} \mathcal{D}'(\Omega, \mathbb{R}^4) \xrightarrow{\text{div}} \mathcal{D}'(\Omega, \mathbb{R}).
\end{align*}
\]
we may study the following sequence with the newly defined curl:
\[
\mathcal{D}'(\Omega, \mathbb{R}) \xrightarrow{\text{grad}} \mathcal{D}'(\Omega, \mathbb{R}^4) \xrightarrow{\text{skw Grad}} \mathcal{D}'(\Omega, \mathbb{K}) \xrightarrow{\text{curl}} \mathcal{D}'(\Omega, \mathbb{R}^4) \xrightarrow{\text{div}} \mathcal{D}'(\Omega, \mathbb{R}).
\]

The properties of the second sequence can be derived from that of the first using
\[
K \text{ skw Grad } u = \text{ Curl } u, \quad \text{curl } \omega = \text{ Div } K \omega
\]
for all \(u \in \mathcal{D}'(\Omega, \mathbb{R}^4)\) and \(\omega \in \mathcal{D}'(\Omega, \mathbb{K})\). In particular, \(\text{skw Grad grad } = 0\), \(\text{curl skw Grad } = 0\) and \(\text{div curl } = 0\).

4.3. Sobolev spaces. In view of the identities of Proposition 10, the spaces \(H(d, \Omega, \mathbb{K}^k)\) in four dimensions are identified to be the same as
\[
H(\text{grad}, \Omega, \mathbb{R}) = \{u \in L^2(\Omega, \mathbb{R}) : \text{ grad } u \in L^2(\Omega, \mathbb{R}^4)\},
\]
\[
H(\text{Curl}, \Omega, \mathbb{R}^4) = \{v \in L^2(\Omega, \mathbb{R}^4) : \text{ Curl } v \in L^2(\Omega, \mathbb{K})\},
\]
\[
H(\text{Div}, \Omega, \mathbb{K}) = \{\kappa \in L^2(\Omega, \mathbb{K}) : \text{ Div } \kappa \in L^2(\Omega, \mathbb{R}^4)\},
\]
\[
H(\text{div}, \Omega, \mathbb{R}^4) = \{q \in L^2(\Omega, \mathbb{R}^4) : \text{ div } q \in L^2(\Omega, \mathbb{R})\},
\]
for \(k = 0, 1, 2, 3\), respectively. Also setting
\[
H(\text{curl}, \Omega, \mathbb{K}) = \{\omega \in L^2(\Omega, \mathbb{K}) : \text{ curl } \omega \in L^2(\Omega, \mathbb{R}^4)\},
\]
we note that the operator \(K\) defined in (40) yields a one-to-one onto homeomorphism \(K : H(\text{curl}, \Omega, \mathbb{K}) \to H(\text{Div}, \Omega, \mathbb{K})\).

In addition to the usual Green’s formula involving gradient and divergence, one can derive other integration by parts formulae, which also clarify the nature of traces in the new spaces. Let \(\mathcal{D}(\bar{\Omega}, \mathbb{K})\) and \(\mathcal{D}(\Omega, \mathbb{R}^4)\) denote the sets of restrictions to \(\Omega\) of functions in \(\mathcal{D}(\mathbb{R}^4, \mathbb{K})\) and \(\mathcal{D}(\mathbb{R}^4, \mathbb{R}^4)\), respectively. Let \(\Omega\) have Lipschitz boundary so that the unit outward normal \(n\) on \(\partial\Omega\) is well defined a.e. Then we can show that the traces \((n \times u)|_{\partial\Omega}\) and \((\omega n)|_{\partial\Omega}\) have meaning for \(u \in H(\text{Curl}, \Omega, \mathbb{R}^4)\) and \(H(\text{Div}, \Omega, \mathbb{K})\). More precisely, define
\[
(\text{tr}^{(1)}u)(\omega) = \int_{\partial\Omega} (n \times u) : \omega, \quad (\text{tr}^{(2)}\omega)(u) = \int_{\partial\Omega} \omega n : u
\]
for all \(u \in \mathcal{D}(\Omega, \mathbb{R}^4)\) and \(\omega \in \mathcal{D}(\Omega, \mathbb{K})\).

**Proposition 11.** Suppose \(\Omega\) has Lipschitz boundary. Then \(\text{tr}^{(1)}\) and \(\text{tr}^{(2)}\) extend to continuous linear operators \(\text{tr}^{(1)} : H(\text{Curl}, \Omega, \mathbb{R}^4) \to H(\text{curl}, \Omega, \mathbb{K})', \) and \(\text{tr}^{(2)} : H(\text{Div}, \Omega, \mathbb{K}) \to H(\text{curl}, \Omega, \mathbb{R}^4)'\) satisfying
\[
(\text{tr}^{(1)}u)(\omega) = \int_{\Omega} \text{Curl } u : \omega - \int_{\Omega} u : \text{curl } \omega
\]
\[
(\text{tr}^{(2)}\kappa)(u) = \int_{\Omega} \text{Div } \kappa \cdot u \, dx - \int_{\Omega} \kappa \times \text{Curl } u
\]
for all \(u \in H(\text{Curl}, \Omega, \mathbb{R}^4)\), \(\kappa \in H(\text{Div}, \Omega, \mathbb{K})\), and \(\omega \in H(\text{curl}, \Omega, \mathbb{K})\).

**Proof.** For \(u \in \mathcal{D}(\Omega, \mathbb{R}^4)\) and \(\omega \in \mathcal{D}(\Omega, \mathbb{K})\), integrating by parts each term that makes up the products below and using the properties of \(\varepsilon\) to simplify the result, we derive
\[
\int_{\Omega} \text{Curl } u : \omega - \int_{\Omega} u \cdot \text{curl } \omega = \int_{\partial\Omega} (n \times u) : \omega.
\]
(42)
Similarly, we also derive
\[ \int_{\Omega} \text{Div} \omega \cdot u - \int_{\Omega} \omega \times \text{Curl} u = \int_{\partial\Omega} \omega n \cdot u. \] (43)

Now viewing \( H(\text{Curl}, \Omega, \mathbb{R}^4), H(\text{Div}, \Omega, \mathbb{K}), \) and \( H(\text{curl}, \Omega, \mathbb{K}) \) as graph spaces of Curl, Div, and curl, we apply the well-known extensions of classical density proofs to graph spaces (see e.g., [23]) to conclude that \( \mathcal{D}(\Omega, \mathbb{R}^4) \) is dense in \( H(\text{Curl}, \Omega, \mathbb{R}^4) \) and that \( \mathcal{D}(\Omega, \mathbb{K}) \) is dense in \( H(\text{curl}, \Omega, \mathbb{K}) \) as well as \( H(\text{Div}, \Omega, \mathbb{K}) \). Hence the result follows from (42) and (43).

The Sobolev spaces we have introduced above have their analogues with essential boundary conditions:

\[ H_0(\text{Curl}, \Omega, \mathbb{R}^4) = \{ v \in H(\text{Curl}, \Omega, \mathbb{R}^4) : \text{tr}^{(1)} v = 0 \}, \]
\[ H_0(\text{Div}, \Omega, \mathbb{K}) = \{ \omega \in H(\text{Div}, \Omega, \mathbb{K}) : \text{tr}^{(2)} \omega = 0 \}. \]

The construction of the HX preconditioner for these spaces follows along the same lines as before using standard preconditioners in \( H_0^1(\Omega) \).

4.4. Finite element spaces. Let \( T \) be a 4-simplex with vertices \( a_i, i = 1, \ldots, 5 \). Let \( \lambda_i \) denote its \( i \)th barycentric coordinate, i.e., \( \lambda_i(x) \) is the unique affine function (of the Euclidean coordinate \( x \) of points in \( T \)) that equals 1 at \( a_i \) and equals 0 at all the remaining vertices of \( T \). Let

\[ g_i = \text{grad} \lambda_i \in \mathbb{R}^4, \quad g_{ij} = g_i \times g_j \in \mathbb{K}, \quad g_{ijk} = g_{ij} g_k \in \mathbb{R}^4. \]

Let \( f_{i_1, \ldots, i_k} \) denote the subsimplex of \( T \) formed by the convex hull of \( a_{i_1}, \ldots, a_{i_k} \) for any \( k = 1, \ldots, 5 \) and let \( \Delta(k, T) \) denote the set of all \( k \)-subsimplices of \( T \). To a 0-subsimplex \( f_i = a_i \) we associate the function \( \lambda_i \) and to other subsimplices \( f_{ij}, f_{ijk} \) and \( f_{ijkl} \), we associate, respectively, the following functions.

\[ \lambda_{ij} = \lambda_i g_j - \lambda_j g_i, \] (44a)
\[ \lambda_{ijk} = \lambda_i g_{jk} - \lambda_j g_{ik} + \lambda_k g_{ij}, \] (44b)
\[ \lambda_{ijkl} = \lambda_i g_{jkl} - \lambda_j g_{ikl} - \lambda_k g_{ijl} + \lambda_l g_{ijk}. \] (44c)

Note that these expressions depend on the ordering of the vertices and on \( T \). When such dependence is to be made explicit, we write the function associated to any \( f_{i_1, \ldots, i_k} \in \Delta(k, T) \), namely \( \lambda_{i_1, \ldots, i_k} \), as \( \lambda_{a_{i_1, \ldots, i_k}} \) or \( \lambda_{a(f)} \) where \( a(f) = (a_{i_1}, \ldots, a_{i_k}) \).

We implemented the lowest order polynomial space \( P_{-1}^k(T) = \text{span}\{ \lambda_{a(f)} : f \in \Delta(k, T) \} \) for \( k = 0, 1, 2 \) and 3. Using Propositions 9 and 10, these spaces may be immediately recognized as the space of proxies of the Whitney basis [2, 43] for \( P_{-1}^k \).

To construct the global finite element spaces, we consider the set of all \( k \)-subsimplices of the simplicial mesh \( \Omega_h \), denoted by \( \Delta(k, \Omega_h) \). An element \( f \) of \( \Delta(k, \Omega_h) \) is in the set \( \Delta(k, T_j) \) for one or more mesh elements \( T_1, \ldots, T_{n_f} \) in \( \Omega_h \). To each \( f \in \Delta(k, \Omega_h) \), we associate an ordered set of its vertices \( a(f) \). The ordering fixes a global orientation of \( f \) independently of \( T_j \). Let \( \lambda_f \), for each \( f \in \Delta(k, \Omega_h) \), be the function that vanishes on all elements of the mesh except \( T_1, \ldots, T_{n_f} \) where its values are given by \( \lambda_f|_{T_j} = \lambda_{a(f)}^T \). These functions define the global finite space by

\[ V_h^{(k)} = \text{span}\{ \lambda_f : f \in \Delta(k, \Omega_h) \} \]
for each $k = 0, 1, 2, 3$. One can easily show that $V_h^{(1)} \subseteq H(\text{Curl}, \Omega, \mathbb{R}^4)$, and $V_h^{(2)} \subseteq H(\text{Div}, \Omega, \mathbb{K})$, either directly integrating by parts using Proposition 11 on each mesh element, or by observing that $V_h^{(k)}$ consists of all proxies of $V_h^{(k)}$ (when $r = 1$) and recalling [2] that $V_h^{(1)} \subseteq H(d, \Omega, \mathbb{R}^4)$. Of course, we also have $V_h^{(0)} \subseteq H(\text{grad}, \Omega, \mathbb{R}^4)$ and $V_h^{(3)} \subseteq H(\text{div}, \Omega, \mathbb{R}^4)$.

Our actual implementation uses an alternate, but equivalent technique that proceeds by implementing the expressions in (44) only on the unit 4-simplex and then mapping the basis functions to each mesh simplex appropriately (see the code in [30] for more details).

4.5. Finite element interpolant. The implementation of the HX preconditioner for $V_h^{(1)} \subseteq H(\text{Curl}, \Omega, \mathbb{R}^4)$, $V_h^{(2)} \subseteq H(\text{Div}, \Omega, \mathbb{K})$, and $V_h^{(3)} \subseteq H(\text{div}, \Omega, \mathbb{R}^4)$ requires us to implement canonical finite element interpolants $\Pi_{h}^{\text{Curl}}$, $\Pi_{h}^{\text{Div}}$, and $\Pi_{h}^{\text{div}}$, into these spaces, respectively. Since the last one is standard, we only describe the first two.

Let $T$ be a 4-simplex with vertices $a_i$ and let $u : T \to \mathbb{R}^4$ be a smooth vector function. Let $e_{ij}$ denote the segment connecting $a_i$ and $a_j$. Then $\Pi_{h}^{\text{Curl}} u|_T$ is the unique function in $P_1^{-1}(T)$ satisfying $\sigma_{ij}(u - \Pi_{h}^{\text{Curl}} u) = 0$ for every edge $e_{ij}$ of $T$, where

$$\sigma_{ij}(u) = \frac{1}{|e_{ij}|} \int_{e_{ij}} u \cdot (a_i - a_j)$$

and $|e_{ij}|$ denotes the length of the edge $e_{ij}$.

Next, let $\omega : T \to \mathbb{K}$ be a smooth function and let $f_{ijk}$ denote the triangle formed by the convex hull of $a_i$, $a_j$, and $a_k$. Then $\Pi_{h}^{\text{Div}} \omega|_T$ is the unique function in $P_1^{-2}(T)$ satisfying $\sigma_{ijk}(\omega - \Pi_{h}^{\text{Div}} \omega) = 0$ for all 2-subsimplices $f_{ijk}$ of $T$, where

$$\sigma_{ijk}(\omega) = \frac{1}{|f_{ijk}|} \int_{f_{ijk}} \omega : (a_j - a_i) \times (a_k - a_i)$$

and $|f_{ijk}|$ denotes the area of the triangle $f_{ijk}$.

To compute the preconditioner action, we need to apply $\Pi_{h}^{\text{Curl}}$ to functions $u : \Omega \to \mathbb{R}^4$ whose components are in the lowest order Lagrange finite element space. Then defining $\Pi_{h}^{\text{Curl}} u|_T$ for each $T$ in $\Omega_h$ as above, the continuity of components of $u$ imply that the resulting global function $\Pi_{h}^{\text{Curl}} u$ in $V_h^{(1)}$. Similarly, when $\omega$ has components in the Lagrange finite element space, $\Pi_{h}^{\text{Div}} \omega$ is in $V_h^{(2)}$.

The unisolvency of these degrees of freedom follow from [3, Theorem 5.5] after identifying the degrees of freedom given there (for $k = 1, 2$) in terms of our proxies using Proposition 9. In particular, $\Pi_{h}^{\text{Curl}}$ and $\Pi_{h}^{\text{Div}}$ can be viewed as proxies of $\Pi_{h}^{(k)}$ for $k = 1$ and 2 in four dimensions.

5. Numerical results

In this section, we report the results of numerical experiments obtained using our implementation of the preconditioners in 4D. We implemented the lowest order finite element subspaces of $H^1(\Omega)$, $H(\text{Curl}, \Omega)$, $H(\text{Div}, \Omega)$ and $H(\text{div}, \Omega)$ on general unstructured (conforming) meshes of 4-simplices. The preconditioners were built atop this discretization. Below we will perform verification of the discretization as well as report on the performance of the preconditioners.
5.1. **Convergence studies.** In the first series of examples, we fix \( \Omega = (0, 1)^4 \) and solve the linear systems arising from the lowest order finite element discretization of the following problem: Find \( u \in H(d, \Omega, \Lambda^k) \), such that

\[
(u, v) + (du, dv) = \langle F, v \rangle \quad \text{for all } v \in H(d, \Omega, \Lambda^k),
\]

where \( F \in H(d, \Omega, \Lambda^k)' \) is a bounded linear functional given below for each \( k = 0, 1, 2, 3 \). The domain \( \Omega \) was initially subdivided into a mesh \( \Omega_h \) of 96 4-simplices of uniform size (see also [33]). Afterwards we apply successive refinement based on the algorithm of Freudenthal (see [7, 15, 33] for more details). The arising linear systems are solved using preconditioned conjugate gradient iterations, where the preconditioner is set to the ones given in §3.1 for each \( k \). In all the presented experiments set the smoother \( D_h \) by three steps of a Chebyshev smoother with respect to the operator \( A \). We iterate until a relative residual error reduction of \( 10^{-6} \) is obtained. Under these numerical settings, we study two types of convergence, namely the convergence rates of the lowest order 4D discretizations, and the iterative convergence of the preconditioned conjugate gradient iterations.

To establish a baseline, we start with 0-forms, i.e. \( d = \text{grad} \). The \( F \) in (45) is set so that the exact solution is

\[
u(x) = \cos(\pi x_1) \cos(\pi x_2) \cos(\pi x_3) \cos(\pi x_4).
\]

The \( L^2(\Omega) \) distance between this \( u \) and the computed solution \( u_h \) in the 4D lowest order Lagrange finite element space is reported in one of the columns of Table 1. Clearly the observed convergence rate is close to two, the best possible rate for this approximation space. For solving the linear systems we set the preconditioner to the algebraic multigrid preconditioner BoomerAMG of the hypre package [18]. The iteration counts reported in the last column of the same table show small iteration numbers with small growth. Recall that one of the basic assumptions in the auxiliary space preconditioner construction is that we have a good preconditioner for the Laplacian. Therefore this report of the performance of BoomerAMG in 4D gives us a measure of how well this baseline assumption is verified in practice.

For 1-forms, i.e. \( d = \text{Curl} \), we set an \( F \) in (45) that yields the exact solution

\[
u(x) = [s_1c_2c_3c_4, -c_1s_2c_3c_4, c_1c_2s_3c_4, -c_1c_2c_3s_4]^{\top},
\]

where \( c_i = \cos(\pi x_i) \) and \( s_i = \sin(\pi x_i) \) for \( i = 1, \ldots, 4 \). In Table 2 we summarize the convergence results for the lowest order finite elements, i.e., edge-elements in 4D. Here, we again observe a convergence rate close to the theoretically expected rate of one. For solving the linear system we use the proposed preconditioner given in Subsection 3.1. Here we obtain small iteration counts. But observe that they are slightly increasing. We believe this is due to the fact that the BoomerAMG’s performance (reported in the previous table) is not strictly uniform.

When considering 2-forms, i.e. \( d = \text{Div} \) we use the manufactured solution

\[
u(x) = \begin{bmatrix}
0 & c_1c_2s_3s_4 & -c_1s_2c_3s_4 & c_1s_2s_3c_4 \\
-c_1c_2s_3s_4 & 0 & s_1c_2c_3s_4 & -s_1c_2s_3c_4 \\
c_1c_2s_3s_4 & -s_1c_2c_3s_4 & 0 & s_1s_2c_3c_4 \\
-c_1s_2s_3c_4 & s_1c_2s_3c_4 & -s_1s_2c_3c_4 & 0
\end{bmatrix},
\]
where $c_i, s_i$ are as above. Using the lowest order finite elements for 2-forms in 4D, we observe in Table 3 the optimal convergence rate of one. Moreover the preconditioner given in Subsection 3.1 leads to similar iteration numbers as in the previous example.

For 3-forms, i.e. $d = \text{div}$ we consider the exact solution

$$u(x) = \begin{bmatrix} c_1 s_2 s_3 s_4, s_1 c_2 s_3 s_4, s_1 s_2 c_3 s_4, s_1 s_2 s_3 c_4 \end{bmatrix}^\top.$$
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For these lowest order Raviart-Thomas finite elements in 4D, we again observe the correct convergence rate of one from Table 4. The iteration numbers for the auxiliary space preconditioner again exhibit a small growth.

5.2. Parameter robustness. In the following experiments we will study the preconditioners when a parameter \( \tau > 0 \) is involved, namely instead of (45), we consider the following problem: Find \( u \in H(d, \Omega, \Lambda_k) \), such that

\[
\tau (u, v) + (du, dv) = \langle F, v \rangle \quad \text{for all } v \in H(d, \Omega, \Lambda_k),
\]
where $F$ is set for each $k$ as described previously. All other parameters, including the domain and stopping criterion, are set as in the previous experiments. The results summarized in Tables 5–8 show iteration numbers for the preconditioned conjugate gradient method. For weights $\tau$ ranging from $10^{-6}$ to $10^6$ we observe quite small iteration numbers which vary only slightly with $\tau$. For small values of $\tau$, these observations are consistent with the analytical conclusions of Theorem 7.

### Conclusion

We presented the auxiliary space preconditioning technique in arbitrary dimensions. The presentation extends previous results of Hiptmair and Xu [21] using the recent results of Costabel and McIntosh [12] and recent developments in finite element exterior calculus [3]. Although, we only analyzed the additive version of the auxiliary space preconditioners, their multiplicative versions can be similarly derived and analyzed.

This work also provides an implementation of the 4D auxiliary space preconditioners (currently available as one of the public domain development branches of [30]). During this work, we also implemented all the finite element spaces (currently the lowest order ones) of the 4D de Rham complex, their canonical interpolants using proxy identities, and attendant 4D mesh operations. Use of this technology for spacetime applications and the addition of geometric multigrid to the tool set are subjects of ongoing research.

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