POLYNOMIAL EXTENSION OPERATORS FOR $H^1$, $H(\text{curl})$ AND $H(\text{div})$ - SPACES ON A CUBE

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Abstract. This paper is devoted to the construction of continuous trace lifting operators compatible with the de Rham complex on the reference hexahedral element (the unit cube). We consider three trace operators: The standard one from $H^1$, the tangential trace from $H(\text{curl})$ and the normal trace from $H(\text{div})$. For each of them we construct a continuous right inverse by separation of variables. More importantly, we consider the same trace operators acting from the polynomial spaces forming the exact sequence corresponding to the Nédélec hexahedron of the first type of degree $p$. The core of the paper is the construction of polynomial trace liftings with operator norms bounded independently of the polynomial degree $p$. This construction relies on a spectral decomposition of the trace data using discrete Dirichlet and Neumann eigenvectors on the unit interval, in combination with a result on interpolation between Sobolev norms in spaces of polynomials.

1. Introduction

Many finite element discretizations of Maxwell’s equations in three space dimensions rely on the reproduction at the discrete level of the exact sequence

\[(1.1) \quad H^1(\Omega) \xrightarrow{\nabla} H(\text{curl}, \Omega) \xrightarrow{\text{curl}} H(\text{div}, \Omega) \xrightarrow{\text{div}} L^2(\Omega).\]

General constructions of finite elements related to (1.1) are analyzed in [21], and a survey on recent discoveries of deeper connections between finite element analysis and exact sequences can be found in [2].

In this paper, we address a central issue in connection with the discretization of (1.1) on a hexahedral mesh by means of the polynomial spaces corresponding to Nédélec’s hexahedron of the first type [24]. The discrete spaces corresponding to (1.1) are built from reference spaces defined on the master hexahedron $\Omega = I \times I \times I$ with $I = (-1, 1)$, forming the exact sequence,

\[(1.2) \quad W_p(\Omega) \xrightarrow{\nabla} Q_p(\Omega) \xrightarrow{\text{curl}} V_p(\Omega) \xrightarrow{\text{div}} Y_p(\Omega).\]

Here $p$ is any positive integer, $W_p(\Omega) = \mathbb{P}^p(I)^{\otimes 3}$, $Q_p(\Omega) = \mathbb{P}^p(I)^{\otimes 3}$, $V_p(\Omega) = W_{p-1}(\Omega)$ and $Y_p(\Omega)$ are suitably defined; see the next section. Combined with suitable inter-element compatibility, the exact polynomial sequence (1.2) mainly serves for...
and \( hp \) versions of finite elements. In order to ensure or control the inter-element compatibility, the trace operators and their right inverses play an important role.

The present work is concerned with the construction of trace liftings at the continuous and polynomial levels, satisfying uniform bounds independently of the degree \( p \). At the continuous level, the trace operators naturally associated with \( H^1(\Omega) \), \( H(\text{curl}, \Omega) \) and \( H(\text{div}, \Omega) \) are the standard trace \( \gamma_0 \), the tangential trace \( \gamma_t \) and the normal trace \( \gamma_n \), respectively. The associated trace spaces are \( H^{1/2}(\partial \Omega) \), \( H^{-1/2}(\text{curl}, \partial \Omega) \) and \( H^{-1/2}(\text{div}, \partial \Omega) \). It is easy to characterize these trace spaces on a cube; see Section 2. For trace spaces defined on general polyhedra, we refer to the work of Buffa and Ciarlet [9], and on general Lipschitz domains to the paper of Buffa, Costabel and Sheen [10].

At the polynomial level, the question is to find extension operators defined on polynomial subspaces of these three trace spaces, which take their values in \( W_p(\Omega) \), \( Q_p(\Omega) \) and \( V_p(\Omega) \), respectively. The construction of such operators becomes a non-trivial task if we request the corresponding norms to be bounded independently of the polynomial degree \( p \). A more demanding task would be to construct extension operators on the continuous spaces that are polynomial preserving; see the work of Schoeberl, Gopalakrishnan and Demkowicz [26].

Existence of polynomial extension operators with \( p \)-independent bounds for the norms is a crucial step in proving convergence for the \( p \) and \( hp \) finite element methods. First, \( H^1 \)-extension operators were constructed by Babuška and Suri in two space dimensions in [4], for both triangular and square elements. Their work was further expanded in [3] and applied to the construction of preconditioners for the \( p \)-method. The 2D constructions remain an active area of research; see the recent results of Ainsworth and Demkowicz [1], and Heuer and Leydecker [18]. Construction of an \( H(\text{curl}) \) extension operator in 2D follows immediately from the corresponding \( H^1 \) operator. The operator was utilized in deriving \( p \)-estimates for the \( H(\text{curl}) \)-conforming problems by Demkowicz and Babuška in [14].

In three space dimensions, there are fewer publications available. For \( H^1 \)-extension operators on the cube, Ben Belgacem [6] has some results, and the recent work by Bernardi, Dauge, and Maday [7] contains some constructions and many estimates in various Sobolev norms. Muñoz-Sola [23] deals with the construction of an \( H^1 \)-operator for a tetrahedron. The incoming contribution of Schoeberl, Gopalakrishnan and Demkowicz [26] presents an alternative construction for the tetrahedron and all spaces forming the exact sequence.

Our construction of \( H^1 \)-, \( H(\text{curl}) \)- and \( H(\text{div}) \)-conforming, polynomial extension operators for a cube mimics closely the corresponding definitions on the continuous level obtained by using the method of separation of variables, and has been stimulated by the work of Pavarino and Widlund [25]. Earlier work on this kind of \( H^1 \)-extension operators was done by Camuto and Funaro [11] and Bernardi and Maday [8]. It has been observed early on that the uniform \( p \)-stability of extension operators is equivalent to certain estimates for \( H^{1/2} \) norms in terms of Hilbert space interpolation of polynomial spaces [21, 6]. A complete proof of such norm estimates is now available [7].

By inspecting our constructions, it turns out that all the lifting operators can be characterized by orthogonality properties or variational principles. One could have used these variational principles to define the liftings. This simple procedure would,
however, not have allowed us to obtain the desired norm bounds independent of the polynomial degree $p$ which we obtain from the explicit constructions.

**Organization of the paper.** In Section 2 we give details of the function spaces which we use, at the continuous as well as at the polynomial level. We define the trace operators. We also recall the Poincaré map. Section 3 deals with questions of continuous and polynomial extension in two dimensions. This serves as a preparatory step for the 3D case. In Section 4 we address the lifting of traces in the continuous and polynomial extension in two dimensions. This serves as a preparatory step for the 3D case. In Sections 5 and 6 we construct polynomial trace liftings into $H^1(\Omega)$ and $H(\text{div}, \Omega)$, with the help of explicit formulæ based on the separation of variables and expansions in bases of discrete 1D Laplace eigenvectors. The Poincaré map then allows us to derive from the previous two liftings the construction of a lifting for $H(\text{curl}, \Omega)$ in Section 7. We emphasize that the direct construction of such a lifting without the help of the Poincaré map would have been a very difficult task. We conclude our paper in Section 8.

2. Sobolev and polynomial spaces

2.1. Sobolev spaces. We use Hörmander’s definitions for all considered Sobolev spaces; see e.g. [22]. The closure of test functions $C_0^\infty(\Omega)$ in $H^s(\mathbb{R}^n)$ is denoted by $\tilde{H}^s(\Omega)$, and for $s \geq -\frac{1}{2}$ can be identified with distributions from $H^s(\Omega)$; see [22]. For Lipschitz domains, $\tilde{H}^s(\Omega)$ and $H^{-s}(\Omega)$ are dual to each other, for any $s \in \mathbb{R}$.

Moreover each scale $(\tilde{H}^s(\Omega))_{s \in \mathbb{R}}$ and $(H^s(\Omega))_{s \in \mathbb{R}}$ is an interpolation scale.

For any $s \geq 0$, the constant functions belong to $H^s(\Omega)$ and to $\tilde{H}^{-s}(\Omega)$. Thus it makes sense to denote by $H^s_{\text{avg}}(\Omega)$ and $\tilde{H}^{-s}_{\text{avg}}(\Omega)$ the functions and distributions with zero average.

We will also use the tensor product form of these spaces, in particular on the square $I \times I = (-1,1)^2$. The space $L^2(I, H^s(I))$ denotes the space of all $L^2$-integrable functions on $I$ with values in the space $H^s(I)$. As a function space on $I \times I$, this space is isomorphic, via an exchange of independent variables, to the space $H^s(I, L^2(I))$ of $L^2(I)$-valued $H^s$ functions on $I$. We will sometimes indicate by indices the coordinates involved, so that we can write $L^2(I_y, H^s(I_x)) = H^s(I_x, L^2(I_y))$. Analogous definitions are used with $\tilde{H}^s$ replacing $H^s$. For any $s \geq 0$, it follows that

\begin{align}
H^s(I \times I) &= L^2(I, H^s(I)) \cap H^s(I, L^2(I)), \\
H^{-s}(I \times I) &= L^2(I, H^{-s}(I)) + H^{-s}(I, L^2(I))
\end{align}

and analogously for $\tilde{H}^{\pm s}$ spaces.

2.2. Trace operators. We denote by $\gamma_0$ the standard trace operator

\begin{equation}
\gamma_0 : H^1(\Omega) \longrightarrow H^\frac{1}{2}(\partial \Omega), \quad U \mapsto u = U|_{\partial \Omega}.
\end{equation}

Here $\Omega$ is a Lipschitz 2D or 3D domain.

In 2D, the space $H(\text{curl}, \Omega)$ is defined as $\{ E \in L^2(\Omega)^2 : \text{curl} E \in L^2(\Omega) \}$, and, in 3D, as $H(\text{curl}, \Omega) = \{ E \in L^2(\Omega)^3 : \text{curl} E \in L^2(\Omega)^3 \}$.
The tangential trace $\gamma_t$ is well defined on $H(\text{curl}, \Omega)$ in 2D and $H(\text{curl}, \Omega)$ in 3D. In 2D, $\gamma_t$ acts continuously from $H(\text{curl}, \Omega)$ into $H^{-\frac{1}{2}}(\partial \Omega)$, and in 3D:

$$\gamma_t : H(\text{curl}, \Omega) \longrightarrow H^{-\frac{1}{2}}(\partial \Omega), \quad E \longmapsto e_t = (E - (E \cdot n)n)|_{\partial \Omega},$$

where $n$ denotes the outward normal unit vector on the boundary $\partial \Omega$. The trace space $H^{-\frac{1}{2}}(\partial \Omega)$ is the space of tangential fields $e \in H^{-\frac{1}{2}}(\partial \Omega)$ such that their surface curls curl$e$ belong to $H^{-\frac{1}{2}}(\partial \Omega)$.

The space $H(\text{div}, \Omega)$ is the space of vector fields $H$ with components in $L^2(\Omega)$ such that div $H \in L^2(\Omega)$. The normal trace $\gamma_n$ is well defined on $H(\text{div}, \Omega)$. In 2D and 3D:

$$\gamma_n : H(\text{div}, \Omega) \longrightarrow H^{-\frac{1}{2}}(\partial \Omega), \quad H \longmapsto h = (H \cdot n)|_{\partial \Omega}.$$

All three trace operators $\gamma_0$, $\gamma_t$ and $\gamma_n$ are surjective [9], and therefore there exist continuous liftings between the spaces in (2.3), (2.4) and (2.5), respectively.

By $H_0^1(\Omega)$, $H_0(\text{curl}, \Omega)$, $H_0(\text{curl}, \Omega)$, $H_0(\text{div}, \Omega)$ we denote the null-spaces of the corresponding trace operators.

2.3. Tensor product polynomial spaces. Let $I = (-1,1)$ be the reference interval. For any integer $p \in \mathbb{N}$ we denote by $\mathbb{P}_p(I)$ the space of polynomials of degree \leq p on I. For $p \geq 2$, let $\mathbb{P}_p(I)$ be the subspace consisting of those $u \in \mathbb{P}_p(I)$ that are zero at ±1.

Let $p, q, r \in \mathbb{N}$. We introduce the tensor product spaces

$$\mathbb{P}^{(p,q)}(I^2) = \mathbb{P}_p(I) \otimes \mathbb{P}_q(I) \quad \text{and} \quad \mathbb{P}^{(p,q,r)}(I^3) = \mathbb{P}_p(I) \otimes \mathbb{P}_q(I) \otimes \mathbb{P}_r(I).$$

Let $\Omega$ be the reference square $(-1,1)^2$ in 2D or the reference cube $(-1,1)^3$ in 3D. The spaces associated with $H^1(\Omega)$ are

$$W_p(I^2) = \mathbb{P}^{(p,p)}(I^2) \quad \text{and} \quad W_p(I^3) = \mathbb{P}^{(p,p,p)}(I^3).$$

The spaces associated with $H(\text{curl}, \Omega)$ and $H(\text{curl}, \Omega)$ are

$$Q_p(I^2) = \mathbb{P}^{(p-1,p)}(I^2) \times \mathbb{P}^{(p,p-1)}(I^2),$$

$$Q_p(I^3) = \mathbb{P}^{(p-1,p,p)}(I^3) \times \mathbb{P}^{(p,p-1,p)}(I^3) \times \mathbb{P}^{(p,p-1,p)}(I^3).$$

In 3D, the spaces associated with $H(\text{div}, \Omega)$ are

$$V_p(I^3) = \mathbb{P}^{(p-1,p-1,p-1)}(I^3) \times \mathbb{P}^{(p-1,p-1,p-1)}(I^3) \times \mathbb{P}^{(p-1,p-1,p-1)}(I^3).$$

Finally the spaces associated with $L^2(\Omega)$ are $Y_p(\Omega) = W_{p-1}(\Omega)$.

Using these spaces, we have for all $p \geq 1$ the following exact sequences:

$$W_p(\Omega) \xrightarrow{\nabla} Q_p(\Omega) \xrightarrow{\text{curl}} Y_p(\Omega) \quad \text{in} \ 2D,$$

$$W_p(\Omega) \xrightarrow{\nabla} Q_p(\Omega) \xrightarrow{\text{curl}} V_p(\Omega) \xrightarrow{\text{div}} Y_p(\Omega) \quad \text{in} \ 3D.$$

2.4. Polynomial traces. Let $p \in \mathbb{N}$. In 2D, we denote by $e_1, \ldots, e_4$ the edges of the square $\Omega = I^2$; see Fig. [4]. We introduce the following two trace spaces:

$$W_p(\partial \Omega) = \{ u \in H^{\frac{1}{2}}(\partial \Omega) : u|_{e_i} \in \mathbb{P}_p(e_i), \ i = 1, \ldots, 4 \},$$

$$Q_p(\partial \Omega) = \{ e \in H^{-\frac{1}{2}}(\partial \Omega) : e|_{e_i} \in \mathbb{P}^{p-1}(e_i), \ i = 1, \ldots, 4 \}.$$
In 3D, we denote by $f_1, \ldots, f_6$ the faces of the cube $\Omega = I^3$; see Fig. 2. We introduce the following three trace spaces:

\begin{align}
W_p(\partial \Omega) &= \{ u \in H^{\frac{1}{2}}(\partial \Omega) : u|_{f_i} \in \mathbb{P}^{p-p}(f_i), \ i = 1, \ldots, 6 \}, \\
Q_p(\partial \Omega) &= \{ e \in H^{-\frac{1}{2}}(\text{curl}, \partial \Omega) : e|_{f_i} \in Q_p(f_i), \ i = 1, \ldots, 6 \}, \\
V_p(\partial \Omega) &= \{ h \in H^{\frac{1}{2}}(\partial \Omega) : h|_{f_i} \in \mathbb{P}^{p-1, p-1}(f_i), \ i = 1, \ldots, 6 \}.
\end{align}

Note that

- In $W_p(\partial \Omega)$, the face traces $u_i := u|_{f_i}$ share common values along the edges of the cube.
- In $Q_p(\partial \Omega)$, the face traces $e_i := e|_{f_i}$ share common values for their tangential traces along the edges of the cube.
- In $V_p(\partial \Omega)$, the face traces $h_i := h|_{f_i}$ are independent of each other.

We end this subsection by the introduction of the polynomial subspaces with zero trace:

\begin{align}
W_{p,0}(\Omega) &= \{ U \in W_p(\Omega) : \gamma_0 U = 0 \} = W_p(\Omega) \cap H_0^1(\Omega), \\
Q_{p,0}(\Omega) &= \{ E \in Q_p(\Omega) : \gamma_1 E = 0 \}.
\end{align}

2.5. **Poincaré map.** Recall the relevant Poincaré map in three space dimensions,

\begin{equation}
K : H(\text{div}, \Omega) \to H(\text{curl}, \Omega), \quad (KH)(x) = -x \times \int_0^1 tH(tx) \, dt.
\end{equation}

For a general definition of the Poincaré map in terms of differential forms in any space dimension, we refer, e.g., to [19] or [2]. Direct, elementary computations (see [17]) show that:

- the map is a right-inverse of the curl operator,

\begin{equation}
\text{div} \, H = 0 \implies \text{curl} \, KH = H,
\end{equation}

- the map is continuous from $H(\text{div}, \Omega)$ into $H(\text{curl}, \Omega)$,

- the map preserves polynomials, i.e. it maps $V_p(\Omega)$ into $Q_p(\Omega)$.

Among other results, the map has been used in [14, 15] to prove that the constant in the discrete Friedrichs’ inequality is independent of the polynomial degree $p$.

### 3. Polynomial extension operators in 2D

In this section we work with the reference square $\Omega = I^2$.

Construction of the polynomial extension operators follows closely the corresponding construction of extension operators on the continuous level by using separation of variables, and we review the continuous case first.

3.1. **Continuous extensions using separation of variables.** We construct extensions on the continuous level for $H^1(\Omega)$ and $H(\text{curl}, \Omega)$.

3.1.1. **$H^1$ extension operator.** Consider $u \in H^{\frac{1}{2}}(\partial \Omega)$. The most natural, finite-energy lift of $u$ is obtained by considering the extension $U \in H^1(\Omega)$ with minimum $H^1$-seminorm. This means that $U$ is the solution of the Dirichlet problem for the homogeneous Laplace equation with boundary data $u$.

We can alternatively construct $U$ through four successive steps involving each time one edge only. We begin by considering restriction $u_3 \in H^{\frac{1}{2}}(e_3)$ of boundary
data $u$ to the third edge. The lift $U_3$ of $u_3$ is constructed by solving the mixed boundary-value problem for the Laplacian,

\begin{equation}
\begin{align*}
U & \in H^1(\Omega), \\
-\Delta U &= 0 \quad \text{in } \Omega, \\
U &= u_3 \quad \text{on edge } e_3, \\
U &= 0 \quad \text{on edge } e_1, \\
\partial_n U &= 0 \quad \text{on edges } e_2, e_4.
\end{align*}
\end{equation}

Here $\partial_n$ is the outer normal derivative. Problem (3.1) is well-posed. Its solution can be represented using the expansion of $u_3$ in the basis of 1D Neumann eigenvectors:

Let $(\Psi_n, \mu_n), n = 0, 1, \ldots$ denote the Neumann eigenpairs for the 1D Laplacian

\begin{equation}
-\Psi''_n = \mu_n \Psi_n, \quad \Psi'_n(-1) = 0, \quad \Psi'_n(1) = 0.
\end{equation}

Eigenvectors are orthogonal in both $L^2$ and $H^1$-products, and we assume that $\Psi_n$ has a unit $L^2$-norm. We write the expansion of $u_3$ as

\begin{equation}
u_3 = \sum_{n=0}^{\infty} u_n \Psi_n(x) \quad \text{with} \quad u_n = \int_{e_3} u(x) \Psi_n(x) \, dx.
\end{equation}

Then we find that $U = U_3$ is given by

\begin{equation}
U_3(x, y) = \sum_{n=0}^{\infty} u_n \Psi_n(x) \beta_n^\mu(y),
\end{equation}

where the corresponding functions $\beta = \beta_n^\mu$ are found by solving the two-point Dirichlet boundary-value problem,

\begin{equation}
-\beta'' + \mu \beta = 0, \quad \beta(-1) = 0, \quad \beta(1) = 1.
\end{equation}

We can check that for $u_3 \in H^2(\Omega)$, the solution lives in $H^1(\Omega)$.

Lift $U_3$ of boundary data $u_3$ vanishes on the first edge, but it does not vanish on the vertical edges. Notice that the use of Neumann boundary conditions on vertical edges is essential. The solution of a problem with homogeneous Dirichlet conditions replacing the Neumann conditions involves, in general, discontinuous Dirichlet data and, therefore, may not live in $H^1(\Omega)$.

We proceed now in a fully analogous way with the first edge and construct lift $U_1$ of restriction $u_1 = u|_{e_1}$ of the boundary data to the first edge.

Next, we subtract from function $u$ traces of lifts $U_3$ and $U_1$, thus

\begin{equation}
v = u - U_1|_{\partial\Omega} - U_3|_{\partial\Omega}.
\end{equation}

Function $v \in H^2(\partial\Omega)$ depends continuously upon the original data $u$ and vanishes on the first and on the third edges. Consequently, its restrictions $v_2, v_4$ to the second and the fourth edge live in $H^2(I)$ with the norm bounded by the $H^2$-norm of the original data $u$.

The fact that the boundary data vanishes at endpoints in a weak sense allows now for considering problems with pure Dirichlet boundary conditions. Lift $U = U_2$
of \( u_2 \) is determined by solving the boundary-value problem

\[
\begin{align*}
U &\in H^1(\Omega), \\
-\Delta U &= 0 \quad \text{in } \Omega, \\
U &= v_2 \quad \text{on edge } e_2, \\
U &= 0 \quad \text{on edges } e_1, e_3, e_4.
\end{align*}
\]

Its solution \( U_2 \) can be represented in terms of 1D Dirichlet eigenpairs \((\Phi_n, \lambda_n), n = 1, 2, \ldots,\)

\[
-\Phi_n'' = \lambda_n \Phi_n, \quad \Phi_n(-1) = \Phi_n(1) = 0
\]

and of the corresponding solutions \( \beta = \beta_n^\lambda \) of the two-point boundary value problem,

\[
-\beta'' + \lambda_n \beta = 0, \quad \beta(-1) = 0, \quad \beta(1) = 1.
\]

\( U_2 \) is given by the formula

\[
(3.10) \quad U_2(x, y) = \sum_{n=1}^{\infty} v_n \beta_n^\lambda(x) \Phi_n(y), \quad u_n = \int_{e_2} v_2 \Phi_n dy.
\]

Lift \( U_4 \) is determined in a fully analogous way. The final \( H^1 \)-extension is computed by summing the four lifts from the individual edges,

\[
(3.11) \quad U = \sum_{j=1}^{4} U_j.
\]

Finally, we record the formulas for the Neumann and Dirichlet eigenpairs,

\[
\Psi_0 = \frac{1}{\sqrt{2}}, \quad \mu_0 = 0, \quad \Psi_n = \cos \left( \frac{n\pi}{2} (x + 1) \right), \quad \mu_n = \frac{n^2\pi^2}{4}, \quad n = 1, 2, \ldots,
\]

\[
\Phi_n = \sin \left( \frac{n\pi}{2} (x + 1) \right), \quad \lambda_n = \frac{n^2\pi^2}{4}, \quad n = 1, 2, \ldots.
\]

Notice that (except for the first Neumann eigenpair) the Neumann and Dirichlet eigenvalues are equal and we have a simple relation,

\[
(3.13) \quad \Phi_n = -\mu_n^{-\frac{1}{2}} \Psi_n', \quad \Psi_n = \lambda_n^{-\frac{1}{2}} \Phi_n'.
\]

Function \( \beta_n^\mu \) is simply linear, and the remaining functions \( \beta_n^\mu, \beta_n^\lambda \) are expressed in terms of exponentials.

Remark 3.1. The global and elementwise constructions of \( U \) result in the same trace lifting, which is the only harmonic \( H^1(\Omega) \) function satisfying the trace condition \( \gamma_0 U = u \). This defines the lift operator \( \mathcal{L}_0 \).

3.1.2. \( H(\text{curl}) \) extension operator. In 2D, the construction of the \( H(\text{curl}) \) extension operator can be reduced to the use of the \( H^1 \)-extension operator. Given a distribution \( e_t \in H^{-\frac{1}{2}}(\partial\Omega) \), we compute first its average,

\[
(3.14) \quad e_0 = (e_t, 1)/8.
\]

Next, we utilize the isomorphism,

\[
(3.15) \quad \partial_1 : H^\frac{1}{2}_{\text{avg}}(\partial\Omega) \rightarrow H^{-\frac{1}{2}}_{\text{avg}}(\partial\Omega)
\]

and introduce the trace potential \( u \in H^\frac{1}{2}_{\text{avg}}(\partial\Omega) \) such that

\[
(3.16) \quad \partial_1 u = e_t - e_0.
\]
Here $\partial_t$ is the derivative along the tangential unit vector field $\mathbf{t}$ such that $(\mathbf{n}, \mathbf{t})$ is direct. The $\mathbf{H}(\text{curl})$-extension is now constructed as follows:

\begin{equation}
E = \nabla U + E_0,
\end{equation}

where $U$ is the $H^1$-extension of the trace potential $u$, and $E_0 \in Q_1(\Omega)$ is e.g. the extension of the constant trace $e_0$ expressed in terms of the lowest-order Nédélec shape functions. As a consequence of the construction above we obtain the estimates

\begin{equation}
\|E\|_{\mathbf{H}(\text{curl}, \Omega)} \leq C \left( \|U\|_{H^1(\Omega)} + \|E_0\|_{\mathbf{H}(\text{curl}, \Omega)} \right) \leq C \left( \|u\|_{H^1(\partial\Omega)} + \|e_0\|_{H^{-\frac{1}{2}}(\partial\Omega)} \right) \leq C \|e_t\|_{H^{-\frac{1}{2}}(\partial\Omega)}.
\end{equation}

Our alternative edgewise construction relies on the fact that the average value need not be evaluated over the whole boundary. This reveals nicely the difference between spaces $H^{-\frac{1}{2}}(I)$ and $\tilde{H}^{-\frac{1}{2}}(I)$. We can consider the restriction of $e_t$ to the third edge. Utilizing the isomorphism

\begin{equation}
\partial : H^{\frac{1}{2}}_{\text{avg}}(I) \to H^{-\frac{1}{2}}(I),
\end{equation}

we introduce the corresponding potential $u_3 \in H^{\frac{1}{2}}_{\text{avg}}(e_3)$ such that $\partial u_3 = e_t|_{e_3}$. The corresponding lift from the edge is defined by taking the gradient of the lift of the potential,

\begin{equation}
E_3 = \nabla u_3.
\end{equation}

Notice that we cannot take the average of functionals from $H^{-\frac{1}{2}}(I)$. In the same way, we construct lift $E_1$. Upon subtracting traces of the lifts from the first and third edges,

\begin{equation}
f_t = e_t - \gamma_t (E_1 + E_3),
\end{equation}

we learn that the corresponding restrictions live in smaller spaces $\tilde{H}^{-\frac{1}{2}}(I)$, for which the computation of the average value is now possible. This can be seen by recalling that space $\tilde{H}^{-\frac{1}{2}}(I)$ is the dual of space $H^{\frac{1}{2}}(I)$, which includes the unit function. Construction of the lift from the second edge is now done similarly to the global construction. Utilizing the isomorphism

\begin{equation}
\partial : H^{\frac{1}{2}}(I) \to \tilde{H}^{-\frac{1}{2}}_{\text{avg}}(I),
\end{equation}

we represent the boundary data as,

\begin{equation}
f_t|_{e_2} = \partial_t u_2 + f_{2,0},
\end{equation}

where $f_{2,0}$ denotes the average value. We then construct the lift by taking

\begin{equation}
E_2 = \nabla U_2 + E_{2,0},
\end{equation}

where $E_{0,2} \in Q_1(\Omega)$ is obtained with the lowest order Nédélec shape function corresponding to the second edge. In the same way, we lift $f_t|_{e_4}$ and define the final lift by summing the four edge contributions,

\begin{equation}
E = \sum_{j=1}^{4} E_j.
\end{equation}
Remark 3.2. Here again, the “global” and “local” constructions result in the same extension operator \( \mathcal{L}_t \), which, moreover, is divergence free. Whatever the construction, we find an extension in the form \( \mathbf{E} = \nabla \mathbf{U} + \mathbf{E}_0 \) where \( \mathbf{U} \in H^1(\Omega) \) is harmonic and \( \mathbf{E}_0 \in Q_1(\Omega) \). Since all elements of \( Q_1(\Omega) \) are divergence free, we find \( \text{div} \mathbf{E} = 0 \). Let us prove that such an extension of the zero tangential trace \( \mathbf{e}_t = 0 \) is zero. Since
\[
\int_{\Omega} \text{curl} \mathbf{E} \, dx \, dy = \int_{\partial \Omega} \mathbf{e}_t \, dt = 0,
\]
we find that the average of \( \text{curl} \mathbf{E}_0 \) on \( \Omega \) is zero. Since \( \text{curl} \mathbf{E}_0 \) is a constant, it is zero. Using the exact sequence \( (3.26) \) we obtain \( \mathbf{U}_0 \in H^1(\Omega) \) such that \( \mathbf{E}_0 = \nabla \mathbf{U}_0 \), and we find that \( \mathbf{E} = \nabla (\mathbf{U} + \mathbf{U}_0) \). Since \( \text{div} \mathbf{E} = 0 \), we find that \( \Delta (\mathbf{U} + \mathbf{U}_0) = 0 \). Since, moreover, \( \gamma_t \nabla (\mathbf{U} + \mathbf{U}_0) = 0 \), we finally deduce that \( \mathbf{U} + \mathbf{U}_0 \) is constant; hence \( \mathbf{E} \) is zero. \( \square \)

Conclusions in 2D continuous case. The lift operators \( \mathcal{L}_0 \) and \( \mathcal{L}_t \) satisfy the following exact sequence and commuting diagram properties:
\[
\begin{align*}
H^1(\Omega) \xrightarrow{\nabla} H(\text{curl}, \Omega) & \xrightarrow{\text{curl}} L^2(\Omega) \\
\gamma_0 \circ \mathcal{L}_0 & \xrightarrow{\gamma_t} \mathcal{L}_t & \gamma_{\text{avg}} \circ \mathcal{L}_{\text{avg}} \\
H^2(\partial \Omega) \xrightarrow{\partial} H^{-1}(\partial \Omega) & \xrightarrow{\gamma_{\text{avg}}} \mathbb{R}
\end{align*}
\] (3.26)
Here, \( \gamma_{\text{avg}} \) is the averaging operator, and \( \mathcal{L}_{\text{avg}} \) is its lifting by a constant function. The operator \( \mathcal{L}_0 \) is uniquely determined by the condition that \( \Delta \circ \mathcal{L}_0 = 0 \), and \( \mathcal{L}_t \) by the conditions that \( \text{div} \circ \mathcal{L}_t \) is zero and that \( \text{curl} \circ \mathcal{L}_t \) takes its values in \( \mathbb{R} \). \( \square \)

3.2. Special families of 1D polynomials. We shall mimic now the continuous construction on the discrete level. We begin by defining a number of polynomial families defined on the master interval \( I = (-1,1) \), with \( p \geq 1 \) denoting a polynomial degree.

Function \( \phi_0^{(p)} \) will denote the minimum \( L^2 \)-norm extension of 0 and 1 values at the interval endpoints in the space of polynomials of order less than or equal to \( p \).

Lemma 3.3. Let \( \phi_0^{(p)} \in \mathbb{P}(I) \) satisfy \( \phi_0^{(p)}(-1) = 0 \) and \( \phi_0^{(p)}(1) = 1 \), with minimum norm in \( L^2(I) \). It follows that
\[
\|\phi_0^{(p)}\|_{L^2(I)}^2 = \frac{2}{p(p+2)}. \tag{3.27}
\]
Proof. See [35, Lemma 1]. \( \square \)

Next we introduce the discrete Dirichlet eigenpairs,
\[
\begin{align*}
\Phi_i & \in \mathbb{P}_i^{(p)}(I) \\
\int_I \Phi_i \Phi_i' &= \lambda_i^{(p)} \int_I \Phi_i v, \quad \forall v \in \mathbb{P}_0^{(p)}(I) \\
i &= 2, \ldots, p
\end{align*}
\] (3.28)
and the discrete Neumann eigenpairs,
\[
\begin{align*}
\Psi_i & \in \mathbb{P}(I) \\
\int_I \Psi_i \Psi_i' &= \mu_i^{(p)} \int_I \Psi_i v, \quad \forall v \in \mathbb{P}(I) \\
i &= 0, \ldots, p
\end{align*}
\] (3.29)
Obviously both eigenvalues and the corresponding eigenvectors depend upon the polynomial degree $p$, $\lambda_i = \lambda_i^{(p)}$, $\Phi_i = \Phi_i^{(p)}$, $\mu_i = \mu_i^{(p)}$, $\Psi_i = \Psi_i^{(p)}$. For simplicity, we will frequently omit the superscript $(p)$, hoping that this does not lead to confusion with the continuous eigenpairs introduced in the previous section.

We shall assume that all discrete eigenvectors have been normalized to have a unit $L^2$-norm,

\begin{equation}
\|\Phi_i\|_{L^2(I)} = 1, \quad \|\Psi_i\|_{L^2(I)} = 1.
\end{equation}

Notice that the first Neumann eigenvalue $\mu_0^{(p)} = 0$, independently of $p$. For each of the discrete Dirichlet and Neumann eigenvalues, we introduce the following solution of the associated discrete 1D boundary-value problem; cf. Section 3.1.

\begin{equation}
\left\{ \begin{array}{l}
\beta_i^\lambda \in \mathbb{P}^p(I), \quad \beta_i^\lambda(-1) = 0, \beta_i^\lambda(1) = 1 \\
\int_I (\beta_i^\lambda v') + \lambda_i^{(p)} \int_I \beta_i^\lambda v = 0 \quad \forall v \in \mathbb{P}^p_0(I) \\
\beta_i^\mu \in \mathbb{P}^p(I), \quad \beta_i^\mu(-1) = 0, \beta_i^\mu(1) = 1 \\
\int_I (\beta_i^\mu v') + \mu_i^{(p)} \int_I \beta_i^\mu v = 0 \quad \forall v \in \mathbb{P}^p(I)
\end{array} \right. \quad (i = 1, \ldots, p).
\end{equation}

Notice that function $\beta_0^\mu$, corresponding to the zero Neumann eigenvalue, is linear for all values of $p$.

**Lemma 3.4.** The inverse inequality

\begin{equation}
|f|_{H^1(I)}^2 \leq \frac{(p+1)^4}{2} \|f\|_{L^2(I)}^2, \quad \forall f \in \mathbb{P}^p(I)
\end{equation}

holds.

**Proof.** See [5].

\[\square\]

**Lemma 3.5.** There exists a constant $C > 0$, independent of $p$, such that

\begin{equation}
\begin{aligned}
|\beta_i^\lambda|_{H^1(I)}^2 + \lambda_i^{(p)} \|\beta_i^\lambda\|_{L^2(I)}^2 &\leq C (\lambda_i^{(p)})^{\frac{1}{2}}, \quad i = 2, \ldots, p, \\
|\beta_i^\mu|_{H^1(I)}^2 + \mu_i^{(p)} \|\beta_i^\mu\|_{L^2(I)}^2 &\leq C (\mu_i^{(p)})^{\frac{1}{2}}, \quad i = 1, \ldots, p.
\end{aligned}
\end{equation}

**Proof.** For completeness, we shall reproduce the reasoning from [25] and prove the second inequality. The proof of the first inequality is fully analogous. Let $i \geq 1$.

- It follows from the definition (3.32) that

\begin{equation}
\begin{aligned}
|\beta_i^\mu|_{H^1(I)}^2 + \mu_i^{(p)} \|\beta_i^\mu\|_{L^2(I)}^2 &\leq |\sigma|_{H^1(I)}^2 + \mu_i^{(p)} \|\sigma\|_{L^2(I)}^2 \\
\forall \sigma &\in \mathbb{P}^p(I) : \sigma(-1) = 0, \sigma(1) = 1.
\end{aligned}
\end{equation}

- Next, we have

\begin{equation}
\begin{aligned}
\mu_i^{(p)} &= \int_I |\Psi_i'|^2 \\
&\leq \frac{(p+1)^4}{2} \quad \text{(set } v = \Psi \text{ in the definition of } \Psi_i)
\end{aligned}
\end{equation}

(Lemma 3.4).
Since \( i \geq 1 \), the discrete eigenvalue \( \mu_i^{(p)} \) is larger than \( \mu_i \), which is in turn larger than or equal to \( \frac{\beta_i^2}{4} > \frac{1}{4} \). Thus we deduce from (3.30) that there exists an integer \( q, 1 \leq q \leq p \) such that

\[
\frac{q^4}{2} \leq \mu_i^{(p)} \leq \frac{(q + 1)^4}{2}.
\]

Now select \( \sigma = \phi_{0}^{(q)} \) with \( \phi_{0}^{(q)} \) defined in Lemma 3.2. We have

\[
|\phi_{0}^{(q)}|_{H^1(I)}^2 + \mu_i^{(p)}|\phi_{0}^{(q)}|_{L^2(I)}^2 \leq (q + 1)^4 |\phi_{0}^{(q)}|_{L^2(I)}^2 \quad \text{(Lemma 3.4)}
\]

\[
\leq 12q^2 \quad \text{(Lemma 3.3)}.
\]

Substituting into (3.35),

\[
|\beta_i^{(p)}|_{H^1(I)}^2 + \mu_i^{(p)}|\beta_i^{(p)}|_{L^2(I)}^2 \leq 12q^2 \leq 12\sqrt{2}(\mu_i^{(p)})^{\frac{1}{2}}.
\]

Notice however that the inequality (3.34) does not hold for index \( i = 0 \), as the first Neumann eigenvalue is equal to zero.

3.3. Construction of the polynomial \( H^1 \) extension operator. We shall consider the master square \( \Omega \) shown in Fig. 1. Let \( u \) belong to the trace space \( W_{p,0}(\partial\Omega) \); cf. (2.11).

Step 1: Lifting from a horizontal edge. We shall consider first the third edge \( e_3 \). Let \( u_3 = u \) be the restriction of \( u \) to \( e_3 \). Then \( u(x) \in \mathbb{P}^p(e_3) \), and we expand it into the discrete Neumann eigenvectors,

\[
\bar{u}(x) = \sum_{j=0}^{p} u_j \Psi_j(x), \quad u_j = \int_I u \Psi_j
\]

and define its polynomial extension as

\[
U(x, y) := \sum_{j=0}^{p} u_j \Psi_j(x) \beta_j^{(p)}(y).
\]

An evaluation of the \( H^1 \)-norm follows, which is straightforward if we use the definition of \( \Psi_j \) and Lemma 3.5:

\[
\int_{\Omega} |\nabla U|^2 = \sum_{i=0}^{p} \sum_{j=0}^{p} u_i u_j \left( \int_I \Psi_i^2 \Psi_j^2 \int_I \beta_i^{(p)} \beta_j^{(p)} + \int_I \Psi_i \Psi_j \int_I (\beta_i^{(p)})^2 (\beta_j^{(p)})^2 \right)
\]

\[
= \sum_{j=0}^{p} |u_j|^2 \left( \mu_j^{(p)} |\beta_j^{(p)}|_{L^2(I)}^2 + |\beta_j^{(p)}|_{H^1(I)}^2 \right)
\]

\[
\leq |u_0|^2 + C \sum_{j=1}^{p} |u_j|^2 (\mu_j^{(p)})^{\frac{1}{2}},
\]

\[
\int_{\Omega} |U|^2 = \sum_{j=0}^{p} |u_j|^2 |\beta_j^{(p)}|_{L^2(I)}^2
\]

\[
\leq C \sum_{j=0}^{p} |u_j|^2.
\]
Consequently,

\[(3.42) \quad \|U\|_{H^1(\Omega)}^2 \leq C \sum_{j=0}^{p} |u_j|^2 \left( 1 + (\mu_j^{(p)})^{\frac{1}{2}} \right).\]

Clearly, the right-hand side of (3.42) is the fractional $\frac{1}{2}$-norm for the polynomial space $\mathbb{P}^p(I)$ obtained by the standard interpolation argument applied to the $L^2$- and the $H^1$-norms and the space of polynomials. The following theorem of Bernardi, Dauge, and Maday provides the key argument for our result.

**Proposition 3.6.** There exists a constant $C > 0$, independent of the polynomial degree $p$, such that

\[(3.43) \quad \|u\|_{\tilde{H}^\frac{1}{2}(e_i)}^2 \leq \sum_{j=0}^{p} |u_j|^2 \left( 1 + (\mu_j^{(p)})^{\frac{1}{2}} \right) \leq C \|u\|_{\tilde{H}^\frac{1}{2}(\partial \Omega)}^2, \quad i = 2, 4.\]

for every polynomial $u \in \mathbb{P}^p(I)$, where $u_j = \int_I u \psi_j^{(p)}$.

**Proof.** See [7, Ch. II, Thm. 4.2].

Consequently, the $H^1$-norm of the lift $U = U_3$ given by (3.31) is bounded by the $\tilde{H}^\frac{1}{2}(e_3)$-norm of trace $u = \tilde{u}_3$, which, in turn, is bounded by the global norm of the trace $u$ on the whole boundary. Notice that, by construction, the lift $U_3$ has a zero trace on the lower edge $e_1$. Repeating thus exactly the same construction for the first edge, we obtain a lift $U_1$ of the trace $\tilde{u}_1$. The polynomial trace

\[(3.44) \quad v = u - \gamma_0(U_1 + U_3)\]

vanishes along the horizontal edges and, consequently, has zero vertex values.

Step 2: Lifting from a vertical edge. We consider now the function $v$ given by (3.44). Its restrictions $v_2$ and $v_4$ to either of the two vertical edges are now bounded in the $\tilde{H}^\frac{1}{2}$-norm,

\[(3.45) \quad \|v_i\|_{\tilde{H}^\frac{1}{2}(e_i)} \leq C \|u\|_{\tilde{H}^\frac{1}{2}(\partial \Omega)}, \quad i = 2, 4.\]
Consider the second edge and expand the function $v_2$ now in terms of the discrete Dirichlet eigenvectors,

$$
(3.46) \quad v_2(y) = \sum_{j=2}^{P} v_j \Phi_j(y), \quad v_j = \int_I v \Phi_j.
$$

The extension $U = U_2$ to the square element is now defined as follows:

$$
(3.47) \quad U(y) = \sum_{j=2}^{P} v_j \beta_j^L(x) \Phi_j(y).
$$

By exactly the same arguments as in the previous paragraph, we show that

$$
(3.48) \quad \|U\|^2_{H^1(\Omega)} \leq C \sum_{j=2}^{P} |v_j|^2 \left(1 + (\lambda_j^{(p)})^{\frac{1}{2}}\right).
$$

The discrete norm on the right-hand side of (3.48) turns out to be equivalent to the continuous $H^{\frac{1}{2}}$-norm.

**Proposition 3.7.** There exists a constant $C > 0$, independent of the polynomial degree $p$, such that

$$
(3.49) \quad \|v\|^2_{H^\frac{1}{2}(I)} \leq \sum_{j=2}^{P} |v_j|^2 \left(1 + (\lambda_j^{(p)})^{\frac{1}{2}}\right) \leq C \|v\|^2_{H^\frac{1}{2}(I)}
$$

for every polynomial $v \in \mathbb{P}_0^p(I)$, where $u_j = \int_I u \Phi_j^{(p)}$.

**Proof.** Such norm equivalences were stated in [6]. For a proof, see [7, Ch. II, Theorem 4.6 and inequality (4.9)].

Notice that the lift does not alter the trace on the remaining edges. Let $U_4$ denote the analogous lift from the vertical edge $e_4$. We have proved

**Theorem 3.8.** The operator

$$
(3.50) \quad \mathcal{L}_0^{(p)} : W_p(\partial \Omega) \ni u \mapsto U := \sum_{j=1}^{4} U_j \in W_p(\Omega)
$$

defines a polynomial lift of traces. Its norm from $H^{\frac{1}{2}}(\partial \Omega)$ into $H^1(\Omega)$ is independent of the degree $p$.

**Remark 3.9.** We can see that for any $u \in W_p(\partial \Omega)$, the lift $\mathcal{L}_0^{(p)} u$ coincides with the solution $U \in W_p(\Omega)$ of the discrete Dirichlet problem

$$
(3.51) \quad \gamma_0 U = u \quad \text{and} \quad \int_{\Omega} \nabla U \cdot \nabla V = 0 \quad \forall V \in W_{p,0}(\Omega).
$$

Thus, despite its nonsymmetric construction, $\mathcal{L}_0^{(p)}$ is canonical. \qed
3.4. Construction of the polynomial \( H(\text{curl}) \) extension operator. Let \( p \geq 1 \) be an integer and let \( \epsilon_t \) be an element of \( Q_p(\partial \Omega) \); cf. (3.14). Using the construction in the continuous case first, we obtain an extension in \( H(\text{curl}, \Omega) \) in the form \( E = \nabla U + E_0 \) with harmonic \( U \in H^1(\Omega) \) and \( E_0 \in Q_1(\Omega) \). We define our polynomial extension \( \mathcal{L}_t^{(p)} \epsilon_t \) by the formula

\[
(3.52) \quad \mathcal{L}_t^{(p)} \epsilon_t = \nabla (\mathcal{L}_0^{(p)} u) + E_0, \quad \text{with } u = \gamma_0 U \in W_p(\partial \Omega).
\]

Indeed we check that

\[
\gamma_t \mathcal{L}_t^{(p)} \epsilon_t = \gamma_t \nabla (\mathcal{L}_0^{(p)} u) + \gamma_t E_0
\]

\[
= \partial_t (\mathcal{L}_0^{(p)} u) \big|_{\partial \Omega} + \gamma_t E_0
\]

\[
= \partial_t u + \gamma_t E_0 = \epsilon_t.
\]

Let us prove furthermore that definition (3.52) is independent of the way that \( E \) is split into \( \nabla U + E_0 \) with harmonic \( U \in H^1(\Omega) \) and \( E_0 \in Q_1(\Omega) \); Let us consider two such representations of \( E, E = \nabla U + E_0 = \nabla U' + E_0' \), with harmonic \( U, U' \in H^1(\Omega) \) and \( E_0, E_0' \in Q_1(\Omega) \). Therefore \( \nabla (U - U') = E_0' - E_0 \). Using the exact sequence (2.9), we find that \( E_0' - E_0 = \nabla U_0 \) with a (harmonic) \( U_0 \in W_1(\Omega) \).

We deduce that, after the possible addition of a constant, \( U - U' = U_0 \). Hence

\[
\nabla \mathcal{L}_0^{(p)} \gamma_0 (U - U') = \nabla \mathcal{L}_0^{(p)} \gamma_0 U_0.
\]

Since \( U_0 \) is a harmonic element of \( W_1(\Omega) \subset W_p(\Omega) \), it satisfies

\[
\mathcal{L}_0^{(p)} \gamma_0 U_0 = U_0.
\]

Finally

\[
\nabla \mathcal{L}_0^{(p)} \gamma_0 (U - U') = \nabla U_0 = E_0' - E_0,
\]

which proves the independence of \( \mathcal{L}_t^{(p)} \epsilon_t \) of the representation of \( E \).

**Theorem 3.10.** The operator

\[
(3.53) \quad \mathcal{L}_t^{(p)} : Q_p(\partial \Omega) \ni \epsilon_t \rightarrow E = \nabla (\mathcal{L}_0^{(p)} u) + E_0 \in Q_p(\Omega)
\]

defines a polynomial lift of tangential traces. Its norm from \( H^{-\frac{1}{2}}(\partial \Omega) \) to \( H(\text{curl}, \Omega) \) is bounded independently of the degree \( p \).

**Proof.** The definition of \( \mathcal{L}_t^{(p)} \) and the fact that it lifts tangential traces are clear from the considerations above. The uniform boundedness with respect to \( p \) is a consequence of estimates (3.18) for the extension in the continuous case, and of the uniform boundedness of the scalar extensions \( \mathcal{L}_0^{(p)} \) (Theorem 3.8). \( \square \)

**Conclusions in 2D polynomial case.** With \( p \geq 1 \) any integer, the lift operators \( \mathcal{L}_0^{(p)} \) and \( \mathcal{L}_t^{(p)} \) satisfy the following exact sequence and commuting diagram properties, reproducing those of the continuous case:

\[
(3.54) \quad \begin{array}{cccccc}
W_p(\Omega) & \xrightarrow{\nabla} & Q_p(\Omega) & \xrightarrow{\text{curl}} & Y_p(\Omega) \\
\gamma_0 \downarrow & & \mathcal{L}_0^{(p)} \downarrow & & \gamma_t \downarrow & \mathcal{L}_t^{(p)} \downarrow & \gamma_{\text{avg}} \downarrow & \mathcal{L}_{\text{avg}} \\
W_p(\partial \Omega) & \xrightarrow{\partial} & Q_p(\partial \Omega) & \xrightarrow{\gamma_{\text{avg}}} & \mathbb{R}
\end{array}
\]

Here, \( \gamma_{\text{avg}} \) is the averaging operator, and \( \mathcal{L}_{\text{avg}} \) is its lifting by a constant function.
The operator $L_0^{(p)}$ is uniquely determined by the extra condition of orthogonality (3.51), and $L_t^{(p)}$ by

$$\int_{\Omega} E \cdot \nabla V = 0 \quad \forall V \in W_{p,0}(\Omega) \quad \text{and} \quad \text{curl} \ E \in \mathbb{R}$$

for $E = L_t^{(p)} e_t$ with $e_t$ any element of $Q_p(\partial \Omega)$. □

4. 3D EXTENSION OPERATORS ON THE CONTINUOUS LEVEL

As in 2D, we will discuss first the construction of the extension operators on the continuous level. In this section, we will use the 1D Dirichlet and Neumann eigenpairs $(\Phi_n, \lambda_n)$ and $(\Psi_n, \mu_n)$ as defined in Section 3.1, equations (3.8) and (3.2).

4.1. $H^1$ extension operator. The procedure is fully analogous to its 2D counterpart. Let $\Omega$ denote the master hexahedron shown in Fig. 2. We begin with the top face $f_2$. Let $u_2 \in H^1_2(f_2)$ denote the restriction of the boundary data $u \in H_2^1(\partial \Omega)$ to face $f_2$. The corresponding lift $U_2$ is constructed by solving the following mixed boundary-value problem for the Laplacian:

$$\begin{cases}
U & \in H^1(\Omega), \\
-\Delta U &= 0 \quad \text{in} \ \Omega, \\
U &= u_2 \quad \text{on face} \ f_2, \\
U &= 0 \quad \text{on face} \ f_1, \\
\partial_n U &= 0 \quad \text{on faces} \ f_3, f_4, f_5, f_6.
\end{cases}$$

Separation of variables leads to two Neumann eigenvalue problems in terms of $x$ and $y$ coordinates, and a two-point Dirichlet boundary-value problem in terms of the coordinate $z$,

$$-\beta'' + (\mu_n + \mu_m)\beta = 0, \quad \beta(-1) = 0, \quad \beta(1) = 1.$$

Functions $\beta = \beta_{nm}^{\mu\mu}$, $n, m = 0, 1, \ldots$ depend upon pairs of Neumann eigenvalues $\mu_n, \mu_m$. The solution $U = U_2$ reads as follows:

$$U_2(x, y, z) = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} u_{nm} \Psi_n(x) \Psi_m(y) \beta_{nm}^{\mu\mu}(z),$$

with $u_{nm} = \int_{f_2} u_2(x, y) \Psi_n(x) \Psi_m(y) \ dy$. In the same way we lift from the bottom face $f_1$. We subtract then the traces of the lifts $U_1, U_2$ from the original boundary data,

$$v = u - (U_1 + U_2)|_{\partial \Omega}.$$

Next, we construct the lifts from the pair of vertical faces $f_3, f_5$. The key point is that, after the subtraction of the first two lifts, function $v$ vanishes over the horizontal faces. Its restriction $v_5$ to face $f_5$ lives in space $H^2( I_x, L^2( I_z)) \cap L^2( I_x, \tilde{H}^2( I_z))$ with the norm controlled by the $H^2$ norm of the original data. Consequently, we

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can impose homogeneous Dirichlet boundary conditions on faces $f_1, f_2$. Lift $U = U_5$ is defined as the solution of the problem

\[
\begin{aligned}
U &\in H^1(\Omega), \\
-\Delta U &= 0 \quad \text{in } \Omega, \\
U &= \psi_5 \quad \text{on face } f_5, \\
U &= 0 \quad \text{on faces } f_1, f_2, f_3, \\
\partial_n U &= 0 \quad \text{on faces } f_4, f_6.
\end{aligned}
\]  

Separation of variables now leads to the Neumann eigenvalue problem in the $x$ coordinate and the Dirichlet eigenvalue problem in the $z$ direction. We need to define a new family of solutions $\beta = \beta_{nm}$ to the two-point boundary-value problem,

\[
-\beta'' + (\mu_n + \lambda_m)\beta = 0, \quad \beta(-1) = 0, \quad \beta(1) = 1.
\]  

The solution $U = U_5$ reads as follows:

\[
U_5(x, y, z) = \sum_{n=0}^{\infty} \sum_{m=1}^{\infty} u_{nm} \Psi_n(x) \beta_{nm}(y) \Phi_m(z)
\]  

with $u_{nm} = \int_{f_5} \psi_5(x, y) \Psi_n(x) \Phi_m(z) \, dx \, dz$.

In the same way we construct lift $U_3$. Upon subtracting lifts $U_3, U_5$, the modified boundary data vanishes over faces $f_1, f_2, f_3, f_5$,

\[
w = u - (U_1 + U_2 + U_3 + U_5)|_{\partial\Omega}.
\]  

Consequently, the traces $w_4$ and $w_6$ of function $w$ on the remaining vertical faces $f_4, f_6$ live in space $H^\frac{1}{2}((I^2))$. We determine lift $U = U_4$ by solving a Dirichlet problem for the Laplacian,

\[
\begin{aligned}
U &\in H^1(\Omega), \\
-\Delta U &= 0 \quad \text{in } \Omega, \\
U &= w_4 \quad \text{on face } f_4, \\
U &= 0 \quad \text{on faces } f_1, f_2, f_3, f_5, f_6.
\end{aligned}
\]

The solution depends continuously on $\|w_4\|_{H^\frac{1}{2}(f_4)}$, which, in turn, is bounded by the $H^1(\partial\Omega)$-norm of the original data. Lift $U_4$ is expressed in terms of Dirichlet eigenfunctions,

\[
U_4(x, y, z) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} u_{nm} \beta_{nm}(x) \Phi_n(y) \Phi_m(z)
\]  

with $u_{nm} = \int_{f_4} w_4(y, z) \Phi_n(y) \Phi_m(z) \, dy \, dz$.

and solutions $\beta = \beta_{nm}$ to the two-point boundary-value problem,

\[
-\beta'' + (\lambda_n + \lambda_m)\beta = 0, \quad \beta(-1) = 0, \quad \beta(1) = 1.
\]
In the same way we construct the lift from face $f_6$. The final extension is constructed by summing the six individual face lifts,

\begin{equation}
U = \sum_{j=1}^{6} U_j.
\end{equation}

**Remark 4.1.** As in 2D this local construction coincides with the global extension operator $L_0$ defined as the Dirichlet harmonic extension. \hfill \Box

4.2. $H(\text{div})$ extension operator. We shall continue now from the other end of the exact sequence. Given a function $h \in H^{-\frac{1}{2}}(\partial \Omega)$, we will construct an extension $H \in H(\text{div}, \Omega)$ such that $\gamma_n H = h$. As in the previous cases, we will work with one face at a time. We first consider the restriction $h_2 = h|_{f_2}$ solve $H = h|_{f_2}$ solve an auxiliary mixed problem for the Laplace operator,

\begin{equation}
\begin{aligned}
&U \in H^1(\Omega), \\
&-\Delta U = 0 \quad \text{in } \Omega, \\
&\partial_n U = h_2 \quad \text{on face } f_2, \\
&\partial_n U = 0 \quad \text{on face } f_1, \\
&U = 0 \quad \text{on faces } f_3, f_4, f_5, f_6.
\end{aligned}
\end{equation}

Notice that, due to the presence of Dirichlet boundary conditions, the Neumann data $h_2$ need not satisfy any compatibility conditions. The lift from face $f_2$ is now set to the gradient of function $U = U_2$,

\begin{equation}
H_2 = \nabla U_2.
\end{equation}

As $U_2$ is harmonic, lift $H_2$ is divergence-free, and its $L^2$-norm, equal to the $H^1$-seminorm of $U_2$, is bounded by the $H^{-\frac{1}{2}}$-norm of data $h_2$. Moreover $U_2$ can be computed using separation of variables,

\begin{equation}
U_2(x, y, z) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} h_{nm} \Phi_n(x) \Phi_m(y) \gamma_{nm}(z),
\end{equation}

with $h_{nm} = \int_{f_2} h_2(x, y, z) \Phi_n(x) \Phi_m(y) \, dx \, dy$.

where $\gamma = \gamma_{nm}$ are solutions to the two-point boundary-value problems with Neumann boundary conditions,

\begin{equation}
-\gamma'' + (\lambda_n + \lambda_m) \gamma = 0, \quad \gamma'(-1) = 0, \quad \gamma'(1) = 1.
\end{equation}

Extension $H_1$ from face $f_1$ is constructed in the same way. Next, we subtract from the original data $h$, the normal traces of the first two face extensions,

\begin{equation}
g = h - \gamma_n (H_1 + H_2)
\end{equation}
and proceed in the same way as for the $H^1$-extensions. Extension $H_5$ is constructed by taking the gradient of solution $U$ to the problem

$$
\begin{align*}
U &\in H^1(\Omega), \\
-\Delta U &= 0 \quad \text{in } \Omega, \\
\partial_n U &= g_5 \quad \text{on face } f_5, \\
\partial_n U &= 0 \quad \text{on faces } f_1, f_2, f_3, \\
U &= 0 \quad \text{on faces } f_4, f_6.
\end{align*}
$$

(4.18)

Here $g_5$ is in the space $H^{-\frac{1}{2}}(I_x, L^2(I_z)) + L^2(I_x, \tilde{H}^{-\frac{1}{2}}(I_z))$, with the corresponding norm controlled by the $H^{-\frac{1}{2}}(\partial \Omega)$-norm of the original data $h$. Solution $U = U_5$ is obtained using the separation of variables,

$$
U_5(x, y, z) = \sum_{n=1}^{\infty} \sum_{m=0}^{\infty} g_{nm} \Phi_n(x) \gamma_{nm} \Psi_m(z),
$$

(4.19)

with $g_{nm} = \int_{f_5} g_5(x, y) \Phi_n(x) \Psi_m(z) \, dx \, dz$,

where $\gamma = \gamma_{nm}$ are solutions to the two-point boundary-value problems with Neumann boundary conditions,

$$
-\gamma'' + (\lambda_n + \mu_m)\gamma = 0, \quad \gamma(-1) = 0, \quad \gamma'(1) = 1.
$$

(4.20)

In the same way we construct lift $H_3$. We subtract then from the original data $h$ normal traces of the four face extensions,

$$
f = h - \gamma_n(H_1 + H_2 + H_3 + H_5).
$$

(4.21)

Functional $f$ vanishes over faces $f_1, f_2, f_3, f_5$. Consequently, its restriction $f_4$ to face $f_4$ lives in space $\tilde{H}^{-\frac{1}{2}}(I^2)$ with the corresponding norm bounded by the $H^{-\frac{1}{2}}(\partial \Omega)$-norm of the original data $h$. For functionals in $\tilde{H}^{-\frac{1}{2}}(I^2)$, we can compute their average values. Let $f_{4,0}$ be the average of $f_4$,

$$
f_{4,0} = \langle f_4, 1 \rangle / 4.
$$

(4.22)

We solve now a pure Neumann problem for $U = U_4$,

$$
\begin{align*}
U &\in H^1(\Omega), \\
-\Delta U &= 0 \quad \text{in } \Omega, \\
\partial_n U &= f_4 - f_{4,0} \quad \text{on face } f_4, \\
\partial_n U &= 0 \quad \text{on faces } f_1, f_2, f_3, f_5, f_6,
\end{align*}
$$

(4.23)

and construct the corresponding face extension as

$$
H_4 = \nabla U_4 + H_{4,0},
$$

(4.24)

where $H_{4,0} \in V_1(\Omega)$ is obtained with the lowest-order Raviart-Thomas shape function for face $f_4$. Function $U = U_4$ is computed using separation of variables,

$$
U_4(x, y, z) = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} f_{nm} \gamma'_{nm}(x) \Psi_n(y) \Psi_m(z),
$$

(4.25)

with $f_{nm} = \int_{f_4} (f_4(x, y) - f_{4,0}) \Psi_n(y) \Psi_m(z) \, dx \, dz$,.
where \( \gamma = \gamma_{nm}^\mu \) are solutions to the two-point boundary-value problems with Neumann boundary conditions,
\[
-\gamma'' + (\mu_n + \mu_m)\gamma = 0, \quad \gamma'(-1) = 0, \quad \gamma'(1) = 1.
\]
In the same way we construct lift \( H_6 \). The final extension, obtained by summing the six face lifts,
\[
(4.27) \quad H = \sum_{j=1}^{6} H_j
\]
is bounded in the \( H(\text{div}, \Omega) \)-norm by the \( H^{-\frac{1}{2}}(\partial \Omega) \)-norm of data \( h \).

We finish this section by recording relations between functions \( \beta \) and \( \gamma \):
\[
(4.28) \quad \begin{align*}
\beta_{nm}^{\lambda\lambda} &= (\gamma_{nm}^\lambda)'', & \beta_{nm}^{\mu\lambda} &= (\gamma_{nm}^\lambda)', & \beta_{nm}^{\mu\mu} &= (\gamma_{nm}^\mu)', \\
\gamma_{nm}^{\lambda\lambda} &= \frac{1}{\lambda_n + \lambda_m} (\beta_{nm}^{\lambda\lambda})', & \gamma_{nm}^{\mu\lambda} &= \frac{1}{\lambda_n + \mu_m} (\beta_{nm}^{\mu\lambda})', & \gamma_{nm}^{\mu\mu} &= \frac{1}{\mu_n + \mu_m} (\beta_{nm}^{\mu\mu})'.
\end{align*}
\]

Remark 4.2. This local construction results in fact in a global extension operator \( \mathcal{L}_n \), which, moreover, is curl free and with constant divergence. Whatever the construction, we find an extension in the form \( H = \nabla U + H_0 \) where \( U \in H^1(\Omega) \) is harmonic and \( H_0 \in V_1(\Omega) \). Since all elements of \( V_1(\Omega) \) are curl free, we find \( \text{curl} H = 0 \). Let us prove that such an extension of the zero normal trace \( h = 0 \) is zero. Since
\[
\int_\Omega \text{div} H \, dx \, dy = \int_{\partial \Omega} h \, dS = 0,
\]
we find that the average of \( \text{div} H_0 \) on \( \Omega \) is zero. Since \( \text{div} H_0 \) is a constant, it is zero; hence \( \text{div} H = 0 \). Using the identity \( \text{curl} H_0 = 0 \) with the exact sequence we obtain \( U_0 \in H^1(\Omega) \) such that \( H_0 = \nabla U_0 \), and we find that \( H = \nabla (U + U_0) \). Since \( \text{div} H = 0 \), we find that \( \Delta (U + U_0) = 0 \). Since, moreover, \( \gamma_n \nabla (U + U_0) = 0 \), we finally deduce that \( U + U_0 \) is constant; hence \( H \) is zero.

4.3. \( H(\text{curl}) \) extension operator. Given a boundary data \( e_t \in H^{-\frac{1}{2}}(\text{curl}, \partial \Omega) \), we are set to construct an extension \( E = \mathcal{L}_n e_t \in H(\text{curl}, \Omega) \) such that \( \gamma_n E = e_t \) and
\[
(4.29) \quad \| E \|_{H(\text{curl}, \Omega)} \leq C \| e_t \|_{H^{-\frac{1}{2}}(\text{curl}, \partial \Omega)}
\]
with constant \( C \) independent of the functional \( e_t \).

We will construct the operator so that we have a commuting diagram property such as in 2D. For this we use the Poincaré map \( K \); see [2.5]. We take the surface curl of the boundary data,
\[
(4.30) \quad h = \text{curl}_{\partial \Omega} e_t,
\]
and consider the corresponding \( H(\text{div}) \)-extension \( H = \mathcal{L}_n h \in H(\text{div}, \Omega) \). Since the average of \( h \) on \( \partial \Omega \) is zero, the divergence of \( H = \mathcal{L}_n h \) is zero.

We then use the Poincaré map \( K \) to pull function \( H \) back into space \( H(\text{curl}, \Omega) \),
\[
(4.31) \quad E_0 = K H.
\]
It follows from the continuity of map \( K \) that \( E_0 \) is bounded in the \( H(\text{curl}, \Omega) \)-norm by the \( H(\text{div}, \Omega) \)-norm of \( H \) and, in turn, by the \( H^{-\frac{1}{2}}(\text{curl}, \partial \Omega) \)-norm of
data \( e_t \). Since \( \text{div} \, H = 0 \), by the fundamental property (2.15) of the Poincaré map we find \( \text{curl} \, E_0 = H \) and, hence, 

\[
(4.32) \quad \text{curl} \, \gamma_n E_0 = \gamma_n \text{curl} \, E_0 = \gamma_n H = h.
\]

After subtracting from \( e_t \) the tangential trace of \( E_0 \), 

\[
(4.33) \quad f_t = e_t - \gamma_t E_0,
\]

the resulting functional \( f_t \) has zero surface curl and it can be identified as the surface gradient of a potential \( u \in H^1_{\text{avg}}(\partial \Omega) \),

\[
(4.34) \quad f_t = \nabla \partial \Omega u.
\]

The potential \( u \) can now be extended to \( U \in H^1(\Omega) \) using the \( H^1 \)-extension operator \( L_0 \), and the final \( H(\text{curl}) \)-extension is defined by summing up the two contributions,

\[
(4.35) \quad E = \nabla U + KH.
\]

Remark 4.3. The use of the Poincaré map \( K \) introduces a “noncanonical” element into this construction. We can get a canonical construction by replacing \( E_0 = KH \) in (4.31) by \( \tilde{E}_0 \) defined by

\[
(4.36) \quad \tilde{E}_0 = KH + \nabla U_0 \quad \text{with} \quad U_0 \in H^1_0(\Omega) \quad \text{such that} \quad \| \tilde{E}_0 \|_{L^2(\Omega)} \quad \text{is minimal.}
\]

The \( H(\text{curl}, \Omega) \) norm of \( \tilde{E}_0 \) is not larger than the one of \( E_0 \), and the lift \( \tilde{E} \) constructed in this way satisfies the orthogonality conditions

\[
(4.37) \quad \int_{\Omega} \text{curl} \, \tilde{E} \cdot \text{curl} \, F = 0 \quad \forall F \in H_0(\text{curl}, \Omega) \quad \text{and} \quad \int_{\Omega} \tilde{E} \cdot \nabla V = 0 \quad \forall V \in H^1_0(\Omega).
\]

It is easy to see that these two orthogonality relations determine \( \tilde{E} \) uniquely. \( \square \)

Conclusions in 3D continuous case. The lift operators \( L_0, L_t \) and \( L_n \) satisfy the following exact sequence and commuting diagram properties:

\[
\begin{array}{cccc}
H^1(\Omega) & \xrightarrow{\nabla} & H(\text{curl}, \Omega) & \xrightarrow{\text{curl} \, K} & H(\text{div}, \Omega) & \xrightarrow{\text{div}} & L^2(\Omega) \\
& \gamma_0 \downarrow \left| \begin{array}{c} L_0 \\ \nabla \end{array} \right| & & \gamma_t \downarrow \left| \begin{array}{c} L_t \\ \nabla \end{array} \right| & & \gamma_n \downarrow \left| \begin{array}{c} L_n \\ \nabla \end{array} \right| & & \gamma_{\text{avg}} \downarrow \left| \begin{array}{c} L_{\text{avg}} \\ \nabla \end{array} \right| & \rightarrow & \mathbb{R} \\
H^{\frac{1}{2}}(\partial \Omega) & \xrightarrow{\nabla} & H^{-\frac{1}{2}}(\text{curl}, \partial \Omega) & \xrightarrow{\text{curl}} & H^{-\frac{1}{2}}(\text{div}, \partial \Omega) & \xrightarrow{\text{div}} & \mathbb{R}
\end{array}
\]

The operator \( L_0 \) is uniquely determined by the condition that \( \Delta \circ L_0 \) is zero, and \( L_n \) by the conditions that \( \text{curl} \circ L_n \) is zero and that \( \text{div} \circ L_n \) takes its values in \( \mathbb{R} \). \( \square \)

5. \( H^1 \) polynomial extension operator in 3D

5.1. Additional 1D polynomials. In this section, we use the notation introduced in Section 3.2 for the discrete 1D Dirichlet eigenpairs \( (\Phi_n, \lambda_n) = (\Phi_n^{(p)}, \lambda_n^{(p)}) \) and for the discrete 1D Neumann eigenpairs \( (\Psi_n, \mu_n) = (\Psi_n^{(p)}, \mu_n^{(p)}) \). On top of the
polynomials discussed in Section 3.2, we need now discrete counterparts of functions $\beta_{\nu \mu}^{nm}, \beta_{\lambda \mu}^{nm}$ and $\beta_{\lambda \lambda}^{nm}$. For each pair of discrete Neumann eigenvalues $\mu_i^{(p)}$ and $\mu_j^{(p)}$, we introduce the corresponding polynomial $\beta_{ij}^{\mu \mu}$ that solves the following 1D variational problem, compare with (3.32),

\[
\begin{aligned}
\beta_{ij}^{\mu \mu} \in \mathbb{P}_p, & \quad \beta_{ij}^{\mu \mu}(-1) = 0, \quad \beta_{ij}^{\mu \mu}(1) = 1 \\
\int_I (\beta_{ij}^{\mu \mu})' v' + (\mu_i^{(p)} + \mu_j^{(p)}) \int_I \beta_{ij}^{\mu \mu} v = 0, & \quad \forall v \in \mathbb{P}_0 \quad (i, j = 0, \ldots, p).
\end{aligned}
\]

In an analogous way, for each couple of Dirichlet eigenvalues, we introduce the corresponding functions $\beta_{ij}^{\lambda \lambda}, i, j = 2, \ldots, p$, and then functions $\beta_{ij}^{\mu \lambda}, i = 0, \ldots, p, j = 2, \ldots, p$, corresponding to pairs $(\mu_i^{(p)}, \lambda_j^{(p)})$.

**Lemma 5.1.** There exists a constant $C > 0$, independent of $p$, such that

\[
\begin{align*}
|\beta_{ij}^{\lambda \lambda}|^2_{H^1(I)} + (\lambda_i^{(p)} + \lambda_j^{(p)}) |\beta_{ij}^{\lambda \lambda}|^2_{L^2(I)} & \leq C \left( \lambda_i^{(p)} + \lambda_j^{(p)} \right)^{1/2}, \\
|\beta_{ij}^{\mu \mu}|^2_{H^1(I)} + (\mu_i^{(p)} + \mu_j^{(p)}) |\beta_{ij}^{\mu \mu}|^2_{L^2(I)} & \leq C \left( \mu_i^{(p)} + \mu_j^{(p)} \right)^{1/2}, \\
|\beta_{ij}^{\mu \lambda}|^2_{H^1(I)} + (\mu_i^{(p)} + \lambda_j^{(p)}) |\beta_{ij}^{\mu \lambda}|^2_{L^2(I)} & \leq C \left( \mu_i^{(p)} + \lambda_j^{(p)} \right)^{1/2},
\end{align*}
\]

$i = 0, \ldots, p, j = 2, \ldots, p$.

**Proof.** The proof is fully analogous to the proof of (3.34). \hfill \Box

### 5.2. Step 1: Lifting from a horizontal face.

Let $u \in W_p(\partial \Omega)$ be a polynomial trace; cf. (2.12). We first consider the horizontal face $z = 1$ of the master cube $\Omega = I^3$; see Fig. 2. Let $u_2(x, y)$ be the restriction of $u$ on this face. We expand it into the discrete 1D Neumann eigenvectors,

\[
(5.2) \quad u_2(x, y) = \sum_{i=0}^{p} \sum_{j=0}^{p} u_{ij} \Psi_i(x) \Psi_j(y),
\]

and define the extension $U = U_2$ as follows:

\[
(5.3) \quad U_2(x, y, z) = \sum_{i=0}^{p} \sum_{j=0}^{p} u_{ij} \Psi_i(x) \Psi_j(y) \beta_{ij}^{\mu \mu}(z).
\]
A straightforward evaluation of the $H^1$-norm gives (we write $\mu_i, \mu_j$ for $\mu_i^{(p)}, \mu_j^{(p)}$)

\begin{align}
\int_{\Omega} |\nabla U|^2 &= \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2 \left( (\mu_i + \mu_j) \|\beta_{ij}^{\mu\mu}\|_{L^2(\Omega)}^2 + |\beta_{ij}^{\mu\mu}\|_{H^1(I)}^2 \right) \\
&= |u_{00}|^2 \|\beta_{00}^{\mu\mu}\|_{H^1(I)}^2 + \sum_{(i,j) \neq (0,0)} \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2 \left( (\mu_i + \mu_j) \|\beta_{ij}^{\mu\mu}\|_{L^2(\Omega)}^2 + |\beta_{ij}^{\mu\mu}\|_{H^1(I)}^2 \right) \\
&\leq 2|u_{00}|^2 + C \sum_{(i,j) \neq (0,0)} \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2 (\mu_i + \mu_j) \frac{1}{2}, \\
\int_{\Omega} |U|^2 &= \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2 \|\beta_{ij}^{\mu\mu}\|_{L^2(I)}^2 \\
&\leq C \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2.
\end{align}

In the last line we have used the fact that all discrete eigenvalues $\mu_i, i > 0$ are greater than the exact eigenvalues and, therefore, are uniformly bounded away from zero, which, by Lemma 5.1 implies that the corresponding $L^2$-norms $\|\beta_{ij}^{\mu\mu}\|_{L^2(I)}^2$ are uniformly bounded. In summary, we have obtained the estimate

\begin{align}
\|U\|_{H^1(\Omega)}^2 &\leq C \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2 \left( 1 + (\mu_i + \mu_j) \frac{1}{2} \right).
\end{align}
Lemma 5.2. The discrete norm on the right-hand side of (5.5) is equivalent to the standard $H^\frac{1}{2}$-norm on the face.

Proof. The standard $L^2$- and $H^1$-norms are equal to the corresponding discrete norms. Thus, by the standard interpolation argument, the continuous $H^\frac{1}{2}$-norm must be bounded by the discrete $H^\frac{1}{2}$-norm. On the other side, by Proposition 3.6 we have

\begin{equation}
(5.6) \quad \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2 \left(1 + \mu_i^\frac{1}{2} + \mu_j^\frac{1}{2} \right) \leq C \|u\|_{L^2(I_x, H^\frac{1}{2}(I_z))}^2,
\end{equation}

and, by the same argument,

\begin{equation}
(5.7) \quad \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2 \left(1 + \mu_i^\frac{1}{2} + \mu_j^\frac{1}{2} \right) \leq C \|u\|_{L^2(I_x, H^\frac{1}{2}(I_z))}^2.
\end{equation}

Summing the last two inequalities we get

\begin{equation}
(5.8) \quad \sum_{i=0}^{p} \sum_{j=0}^{p} |u_{ij}|^2 \left(1 + (\mu_i + \mu_j)^\frac{1}{2} \right) \leq C(\|u\|_{L^2(I_x, H^\frac{1}{2}(I_z))}^2 + \|u\|_{L^2(I_x, H^\frac{1}{2}(I_z))}^2) \approx \|u\|_{H^\frac{1}{2}(I_z)}^2 \quad \square
\end{equation}

In conclusion, the $H^1$-norm of extension $U = U_2$ is bounded by the $H^\frac{1}{2}$-norm of the data $u$. In exactly the same way, we construct an extension $U_1$ from the lower face $z = -1$. Notice that both extensions are zero on the opposite face and, therefore, do not alter the original values there.

5.3. Lifting from the vertical faces. We proceed now along the lines of the construction on the continuous level discussed in Section 4.1. Let $U_1$ and $U_2$ denote the extensions from the lower and the upper horizontal faces, respectively. We consider the trace

\begin{equation}
(5.9) \quad v = v(x, z) = (u - U_1 - U_2)(x, 1, z).
\end{equation}

Function $u - U_1 - U_2$ vanishes over the horizontal faces and, therefore, the trace $v$ is bounded in the norm of the $H^\frac{1}{2}(I_x, L^2(I_z)) \cap L^2(I_x, H^\frac{1}{2}(I_z))$ space. We expand function $v$ now in the products of discrete Neumann and Dirichlet eigenvectors,

\begin{equation}
(5.10) \quad v(x, z) = \sum_{i=0}^{p} \sum_{j=2}^{p} v_{ij} \Psi_i(x) \Phi_j(z),
\end{equation}

and define extension $U = U_5$ as

\begin{equation}
(5.11) \quad U_5(x, y, z) = \sum_{i=0}^{p} \sum_{j=2}^{p} v_{ij} \Psi_i(x) \beta_{ij}^\alpha(y) \Phi_j(z).
\end{equation}

Following the same steps as in the previous section, we demonstrate that the $H^1$-norm of extension $U_5$ is bounded by the $H^\frac{1}{2}(I_x, L^2(I_z)) \cap L^2(I_x, H^\frac{1}{2}(I_z))$-norm of trace $v$ and, consequently, by the $H^\frac{1}{2}$-norm of the trace $u$ on the whole boundary. Then, in the same way, we construct lift $U_3$ from face $y = -1$. 
Having constructed the lifts $U_3$ and $U_5$ from the third and the fifth face, we subtract them from $u - U_1 - U_2$ and consider the trace of the remaining function on face $x = 1$,

\begin{equation}
\tag{5.12}
w(y, z) = (u - U_1 - U_2 - U_3 - U_5)(1, y, z).
\end{equation}

As function $u - U_1 - U_2 - U_3 - U_5$ vanishes over faces 1, 2, 3 and 5, the trace $v$ is bounded in the $\tilde{H}^{1/2}$-norm. We expand it into the discrete Dirichlet eigenvectors,

\begin{equation}
\tag{5.13}
w(x, z) = \sum_{i=2}^{p} \sum_{j=2}^{p} w_{ij} \Phi_i(y) \Phi_j(z),
\end{equation}

and define the extension as

\begin{equation}
\tag{5.14}
U_4(x, y, z) = \sum_{i=2}^{p} \sum_{j=2}^{p} w_{ij} \beta_{ij}(x) \Phi_i(y) \Phi_j(z).
\end{equation}

Again, following the same steps as in the previous section, we demonstrate that the $H^1$-norm of extension $U_4$ is bounded by the $\tilde{H}^{1/2}(I^2)$-norm of trace $v$ and, consequently, by the $H^{1/2}$-norm of the trace $u$ on the whole boundary. Then, in the same way, we construct the lift $U_6$ from face $x = -1$. The final extension is defined as the sum of the contributions from the six faces, and we have proved

**Theorem 5.3.** On the cube $\Omega = I^3$, the operator

\begin{equation}
\tag{5.15}
\mathcal{L}^{(p)}_0 : W_p(\partial \Omega) \ni u \mapsto U := \sum_{j=1}^{6} U_j \in W_p(\Omega)
\end{equation}

defines a polynomial lift of traces. Its norm from $H^{1/2}(\partial \Omega)$ into $H^1(\Omega)$ is bounded independently of the degree $p$.

6. $H(\text{div})$ POLYNOMIAL EXTENSION OPERATOR IN 3D

Before we proceed along the lines outlined in Section 4.2, we make one important modification. Motivated with relations (4.28) between functions $\gamma$ and $\beta$ on the continuous level, we shall replace all functions $\gamma$ (that have not been defined on the discrete level at all) with derivatives of the corresponding functions $\beta$ and, similarly, express 1D Neumann eigenvectors with the derivatives of Dirichlet eigenvectors, and 1D Dirichlet eigenvectors with the derivatives of Neumann eigenvectors. Throughout this section, we use the condensed notation $(\Phi_n, \lambda_n)$ and $(\Psi_n, \mu_n)$ for the discrete 1D Dirichlet and Neumann eigenpairs introduced in Section 3.2.

6.1. Step 1: Lifting from a horizontal face. Let $h$ be a polynomial trace in the trace space $V_p(\partial \Omega)$; see (2.12). We begin with the restriction $h_{y2}$ of function $h$ to the second face. This restriction belongs to $\mathbb{P}^{p-1} \otimes \mathbb{P}^{p-1}$. We expand it in terms of derivatives of the discrete 1D Neumann eigenvectors,

\begin{equation}
\tag{6.1}
h_{y2}(x, y) = \sum_{n=1}^{p} \sum_{m=1}^{p} h_{nm} \frac{\Psi_n'(x)}{\mu_n} \frac{\Psi_m'(y)}{\mu_m}.
\end{equation}
Notice that the functions $\mu_n^{-\frac{1}{2}} \Psi_n'$ are $L^2$-orthonormal. The vector-valued extension $H = H_2$ is now defined as follows:

$$H_2 = \left\{ \begin{array}{l}
- \sum_{n=1}^{p} \sum_{m=1}^{p} h_{nm} \mu_n \frac{1}{\mu_n} \Psi_n(x) \frac{1}{\mu_m} \Psi_m(y) (\beta_{nm}^\mu)'(z), \\
- \sum_{n=1}^{p} \sum_{m=1}^{p} h_{nm} \frac{1}{\mu_n} \Psi_n(x) \frac{1}{\mu_m} \Psi_m(y) (\beta_{nm}^\mu)'(z), \\
\sum_{n=1}^{p} \sum_{m=1}^{p} h_{nm} \frac{1}{\mu_n} \Psi_n(x) \frac{1}{\mu_m} \Psi_m(y) \beta_{nm}^\mu(z) \right\}.
\end{array} \right.$$

(6.2)

Notice a direct correspondence of Formula (6.2) with the gradient of function (4.15) with the replacements outlined in the beginning of this section.

A direct calculation reveals that polynomial $H_2$ is divergence-free. The $H$-(div)-norm of function $H_2$ reduces then to its $L^2$-norm, which we now calculate. Utilizing the $L^2$-orthogonality of eigenvectors $\Psi_n$ and their derivatives, we obtain

$$\|H_2\|^2_{L^2(\Omega)} = \sum_{n=1}^{p} \sum_{m=1}^{p} |h_{nm}|^2 \left( \frac{1}{\mu_n + \mu_m} \| (\beta_{nm}^\mu)' \|_{L^2(I)}^2 + \| \beta_{nm}^\mu \|^2_{L^2(I)} \right).$$

(6.3)

Making use of Lemma 5.1 we obtain the bound

$$\|H_2\|^2_{L^2(\Omega)} \leq C \sum_{n=1}^{p} \sum_{m=1}^{p} |h_{nm}|^2 (\mu_n + \mu_m)^{-\frac{1}{2}}.$$

(6.4)

It remains to show now that the weighted sum on the right-hand side is equivalent to the $H^{-\frac{1}{2}}$-norm of data $h_2$. We begin with a simple result concerning the $H^{-\frac{1}{2}}$-norm in one space dimension.

**Lemma 6.1.** Let $w \in \mathbb{P}^{p-1}$ be expanded in terms of the derivatives of discrete Neumann eigenvectors,

$$w = \sum_{n=1}^{p} w_n \frac{\Psi_n'}{\mu_n^{\frac{1}{2}}}.$$

The following discrete norm is equivalent to the $H^{-\frac{1}{2}}$-norm of $w$ with equivalence constants independent of the degree $p$,

$$\|w\|^2_{H^{-\frac{1}{2}}(I)} \approx \sum_{n=1}^{p} |w_n|^2 \mu_n^{-\frac{1}{2}}.$$

(6.6)

Proof. The proof follows from the isomorphism,

$$\partial : H^{\frac{1}{2}}_{\text{avg}}(I) \rightarrow H^{-\frac{1}{2}}(I)$$

and Proposition 3.6.

We can prove now a similar result for two space dimensions.

**Lemma 6.2.** Let polynomial $h \in \mathbb{P}^{p-1} \otimes \mathbb{P}^{p-1}$ be expanded in terms of the derivatives of the discrete Neumann eigenvectors as in Formula (6.1). The discrete norm (6.4) is equivalent to the $H^{-\frac{1}{2}}$-norm of $h$ with equivalence constants independent of the degree $p$.
Proof. We begin by recalling the standard tensorization result for the space $H^{-\frac{1}{2}}(I^2)$,

\begin{equation}
H^{-\frac{1}{2}}(I^2) = L^2(I_x, H^{-\frac{1}{2}}(I_y)) + L^2(I_y, H^{-\frac{1}{2}}(I_x)),
\end{equation}

where

\begin{equation}
L^2(I_x, H^{-\frac{1}{2}}(I_y)) := \{ h(x, y) : \int_I \| h(x, \cdot) \|_{H^{-\frac{1}{2}}(I)}^2 \, dx < \infty \}
\end{equation}

with an analogous definition for the second space. The norm in the sum of two

\begin{equation}
\| h \|_{L^2(I_x, H^{-\frac{1}{2}}(I_y))} \approx \sum_{n=1}^p \sum_{m=1}^p | h_{nm} |^2 \mu_m^{-\frac{1}{2}},
\end{equation}

\begin{equation}
\| h \|_{L^2(I_y, H^{-\frac{1}{2}}(I_x))} \approx \sum_{n=1}^p \sum_{m=1}^p | h_{nm} |^2 \mu_n^{-\frac{1}{2}}.
\end{equation}

Finally, definition \((6.10)\) and elementary algebraic arguments lead to

\begin{equation}
\| h \|_{H^{-\frac{1}{2}}(I^2)} = \inf_{u_{nm} + v_{nm} = h_{nm}} \left( \sum_{n=1}^p \sum_{m=1}^p | u_{nm} |^2 \mu_m^{-\frac{1}{2}} + \sum_{n=1}^p \sum_{m=1}^p | v_{nm} |^2 \mu_n^{-\frac{1}{2}} \right)
\end{equation}

\begin{equation}
\approx \sum_{n=1}^p \sum_{m=1}^p | h_{nm} |^2 \min\{ \mu_m^{-\frac{1}{2}}, \mu_n^{-\frac{1}{2}} \}
\end{equation}

\begin{equation}
\approx \sum_{n=1}^p \sum_{m=1}^p | h_{nm} |^2 (\mu_n + \mu_m)^{-\frac{1}{2}}.
\end{equation}

Here sign $A \approx B$ indicates the existence of constants $C_1, C_2$ independent of the function $h$ and the polynomial degree $p$, such that $A \leq C_1 B$ and $B \leq C_2 A$. \hspace{1cm} \Box

We have demonstrated therefore the continuity of the lift operator,

\begin{equation}
\| H \|_{H^{1}(\Omega)} \leq C \| h_2 \|_{H^{-\frac{1}{2}}(I^2)}.
\end{equation}

In the same way we construct then the lift from the bottom face $f_1$.

6.2. Step 2: Lifting from faces $f_3, f_5$. We mimic the construction on the continuous level. First normal traces of lifts $H_1, H_2$ are subtracted from the original data,

\begin{equation}
g := h - \gamma_n(H_1 + H_2).
\end{equation}

Restriction $g_5$ of polynomial $g$ to face $f_5$ is expanded in terms of derivatives of the discrete 1D Neumann and Dirichlet eigenvectors,

\begin{equation}
g_5(x, z) = \sum_{n=1}^p g_n \frac{\Psi_n'(x)}{\mu_n^\frac{1}{2}} \frac{1}{\sqrt{2}} + \sum_{n=1}^p \sum_{m=2}^p g_{nm} \frac{\Psi_n'(x)}{\mu_n^\frac{1}{2}} \frac{\Phi_m'(z)}{\lambda_m^\frac{1}{2}}.
\end{equation}
Notice that the functions $\lambda_m^{\frac{1}{2}} \Phi_m$, $m = 2, \ldots, p$, complemented with constant $1/\sqrt{2}$, are $L^2$-orthonormal. The vector-valued extension $H = H_5$ is now defined as follows:

(6.16) \[ H_5 = \left( -\sum_{n=1}^{p} g_{n1} \mu_n^\frac{1}{2} \Psi_n(x) \left( \frac{\beta_{nm}^\mu(y)}{\mu_n} \right) \frac{1}{\sqrt{2}} - \sum_{n=1}^{p} \sum_{m=2}^{p} \mu_n \Psi_n(x) \left( \frac{\beta_{nm}^{\mu_\lambda}(y)}{\mu_n + \lambda_m} \right) \frac{1}{\sqrt{2}} \right. \]

\[ - \sum_{n=1}^{p} \sum_{m=2}^{p} g_{nm} \mu_n \Psi_n(x) \left( \frac{\beta_{nm}^{\mu_\lambda}(y)}{\mu_n + \lambda_m} \right) \frac{1}{\sqrt{2}} \left. \right) \times \frac{1}{\sqrt{2}} ] \]

A direct computation reveals that $H_5$ is divergence-free. We proceed with the evaluation of the $L^2$-norm,

\[ \| H_5 \|^2_{L^2(I)} = \sum_{n=1}^{p} |g_{n1}|^2 \left( \frac{1}{\mu_n} \right) \| \frac{\beta_{nm}^\mu}{\mu_n} \|_{L^2(I)}^2 + \frac{1}{\lambda_m} \| \frac{\beta_{nm}^{\mu_\lambda}}{\mu_n + \lambda_m} \|_{L^2(I)}^2 \]

\[ \leq C \left( \sum_{n=1}^{p} |g_{n1}|^2 \mu_n^{-\frac{1}{2}} + \sum_{n=1}^{p} \sum_{m=2}^{p} |g_{nm}|^2 (\mu_n + \lambda_m)^{-\frac{1}{2}} \right) \]

where, in the last inequality, we have used Lemma 6.3 and Lemma 6.4. We continue now with a result concerning the $H^{-\frac{1}{2}}$-norm in one space dimension.

**Lemma 6.3.** Let $w \in \mathbb{P}^{p-1}$ be expanded in terms of the derivatives of discrete Dirichlet eigenvectors and a constant function,

(6.18) \[ w = w_1 \frac{1}{\sqrt{2}} + \sum_{m=2}^{p} w_m \frac{\Phi_m}{\lambda_m^\frac{1}{2}}. \]

The following discrete norm is equivalent to the $H^{-\frac{1}{2}}$-norm of $w$ with equivalence constants independent of the degree $p$,

(6.19) \[ \| w \|^2_{H^{-\frac{1}{2}}(I)} \approx |w_1|^2 + \sum_{m=2}^{p} |w_m|^2 \lambda_m^{-\frac{1}{2}}. \]

**Proof.** The proof follows from the stable decomposition

(6.20) \[ \tilde{H}^{-\frac{1}{2}}(I) = \mathbb{C} \oplus \tilde{H}_{avg}^{-\frac{1}{2}}(I), \quad w = w_0 + (w - w_0), \quad w_0 = \langle w, 1 \rangle / 2, \]

the isomorphism

(6.21) \[ \partial : \tilde{H}^{\frac{1}{2}}(I) \to \tilde{H}_{avg}^{-\frac{1}{2}}(I), \]

and Proposition 3.7. \[ \square \]

We have now a discrete version of the norm in $H^{-\frac{1}{2}}(I_x, L^2(I_z)) + L^2(I_x, \tilde{H}^{-\frac{1}{2}}(I_z))$.

**Lemma 6.4.** Let $h \in \mathbb{P}^{p-1} \otimes \mathbb{P}^{p-1}$ be a polynomial expanded in terms of derivatives of discrete Neumann and Dirichlet eigenvectors as in Formula (6.15). The
following discrete norm is equivalent to the norm in the space $H^{-\frac{1}{2}}(I_x, L^2(I_z)) + L^2(I_x, H^{-\frac{1}{2}}(I_z))$ with equivalence constants independent of the polynomial degree $p$:

\begin{equation}
\|h\|^2 = \sum_{n=1}^{p} |g_{n1}|^2 \mu_n^{-\frac{1}{2}} + \sum_{n=1}^{p} \sum_{m=1}^{p} |g_{nm}|^2 (\mu_n + \lambda_m)^{-\frac{1}{2}}.
\end{equation}

\textbf{Proof.} Lemma 6.3 implies that

\begin{equation}
\|h\|^2_{L^2(I_x, H^{-\frac{1}{2}}(I_z))} \approx \sum_{n=1}^{p} |g_{n1}|^2 \mu_n^{-\frac{1}{2}} + \sum_{n=1}^{p} \sum_{m=1}^{p} |g_{nm}|^2 \lambda_m^{-\frac{1}{2}}
\end{equation}

and from Lemma 6.1 it follows that

\begin{equation}
\|h\|^2_{L^2(I_x, H^{-\frac{1}{2}}(I_z))} \approx \sum_{n=1}^{p} |g_{n1}|^2 \mu_n^{-\frac{1}{2}} + \sum_{n=1}^{p} \sum_{m=1}^{p} |g_{nm}|^2 \mu_n^{-\frac{1}{2}}.
\end{equation}

As discrete eigenvalues, the $\mu_n$ are always greater than their exact counterparts, and only a finite number of Neumann eigenvalues is less than one. We have

\begin{equation}
\|h\|^2 \approx \sum_{n=1}^{p} |g_{n1}|^2 \min\{1, \mu_n^\frac{1}{2}\} + \sum_{n=1}^{p} \sum_{m=1}^{p} |g_{nm}|^2 \min\{\mu_n^\frac{1}{2}, \lambda_m^\frac{1}{2}\}
\end{equation}

\begin{equation}
\approx \sum_{n=1}^{p} |g_{n1}|^2 \mu_n^{-\frac{1}{2}} + \sum_{n=1}^{p} \sum_{m=1}^{p} |g_{nm}|^2 (\mu_n + \lambda_m)^{-\frac{1}{2}},
\end{equation}

which ends the proof.

Thus, we have shown that the $\mathbf{H}(\text{div}, \Omega)$-norm of extension $\mathbf{H}_5$ is bounded by the norm of the face data $g_{n1}$ in the space $H^{-\frac{1}{2}}(I_x, L^2(I_z)) + L^2(I_x, H^{-\frac{1}{2}}(I_z))$, and in turn, by the $H^{-\frac{1}{2}}(\partial\Omega)$-norm of the original boundary data $h$. The lift from face $f_3$ is constructed in the same way.

\section{Step 3: Lifting from faces $f_4$, $f_6$.}

We again mimic the construction of the continuous level. Normal traces of lifts $\mathbf{H}_4, \mathbf{H}_2, \mathbf{H}_3, \mathbf{H}_5$ are subtracted from the original data,

\begin{equation}
f := h - \gamma_n(\mathbf{H}_4 + \mathbf{H}_2 + \mathbf{H}_3 + \mathbf{H}_5).
\end{equation}

The restriction $f_4$ of polynomial $f$ to face $f_4$ is expanded in terms of derivatives of the discrete 1D Dirichlet eigenvectors and constant functions,

\begin{equation}
f_4(y, z) = f_{11} \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} + \sum_{n=2}^{p} f_{n1} \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} + \sum_{m=2}^{p} f_{1m} \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} + \sum_{n=2}^{p} \sum_{m=2}^{p} f_{nm} \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}}.
\end{equation}

As $f_4$ is now controlled in the $H^{-\frac{1}{2}}(I^2)$-norm, the average value $f_{11}$ of $f_4$ depends continuously upon the norm, and the corresponding constant function is extended into the element using the lowest-order Raviart-Thomas shape function $\mathbf{H}_{RT,4}$. We proceed by defining extension $\mathbf{H} = \mathbf{H}_4$ of function $f_4$ with the constant $f_{11}$.

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removed:

\[
H_x = \sum_{n=2}^{p} f_{n1} \frac{\beta_n^\lambda}{\lambda_n^2} \Phi_n'(y) \frac{1}{\sqrt{2}} + \sum_{m=2}^{p} f_{1m} \frac{\beta_m^\lambda}{\lambda_m^2} \Phi_m'(z)
\]

\[
+ \sum_{n=2}^{p} \sum_{m=2}^{p} f_{nm} \frac{\beta_{nm}^\lambda}{\lambda_n + \lambda_m} \Phi_n'(y) \frac{1}{\sqrt{2}} \Phi_m'(z),
\]

\[
H_y = -\sum_{n=2}^{p} f_{n1} \frac{1}{\lambda_n} (\beta_n^\lambda)'(x) \frac{1}{\sqrt{2}} \Phi_n(y)
\]

\[
- \sum_{n=2}^{p} \sum_{m=2}^{p} f_{nm} \frac{1}{\lambda_n + \lambda_m} (\beta_{nm}^\lambda)'(x) \lambda_n \Phi_n'(y) \frac{1}{\lambda_m^2} \Phi_m'(z),
\]

\[
H_z = -\sum_{m=2}^{p} f_{1m} \frac{1}{\lambda_m} (\beta_m^\lambda)'(y) \frac{1}{\sqrt{2}} \lambda_m \Phi_m(z)
\]

\[
- \sum_{n=2}^{p} \sum_{m=2}^{p} f_{nm} \frac{1}{\lambda_n + \lambda_m} (\beta_{nm}^\lambda)'(x) \frac{1}{\lambda_m^2} \Phi_n'(y) \lambda_n \Phi_m'(z).
\]

A direct computation shows again that \(\text{div} \, \mathbf{H} = 0\). We proceed with the evaluation of the \(L^2\)-norm,

\[
\| \mathbf{H} \|_{L^2(\Omega)}^2 = \sum_{n=2}^{p} |f_{n1}|^2 \left( \frac{1}{\lambda_n} \| (\beta_n^\lambda)' \|_{L^2(I)} + \frac{\| \beta_n^\mu \|_{L^2(I)}^2}{\| \beta_n^\mu \|_{L^2(I)}} \right)
\]

\[
+ \sum_{m=2}^{p} |f_{1m}|^2 \left( \frac{1}{\lambda_m} \| (\beta_m^\lambda)' \|_{L^2(I)} + \frac{\| \beta_m^\mu \|_{L^2(I)}^2}{\| \beta_m^\mu \|_{L^2(I)}} \right)
\]

\[
+ \sum_{n=2}^{p} \sum_{m=2}^{p} |f_{nm}|^2 \left( \frac{1}{\lambda_n + \lambda_m} \| (\beta_{nm}^\lambda)' \|_{L^2(I)}^2 + \frac{\| \beta_{nm}^\mu \|_{L^2(I)}^2}{\| \beta_{nm}^\mu \|_{L^2(I)}} \right)
\]

\[
\leq C \left( \sum_{n=2}^{p} |f_{n1}|^2 \lambda_n^{-\frac{1}{2}} + \sum_{m=2}^{p} |f_{1m}|^2 \lambda_m^{-\frac{1}{2}} + \sum_{n=2}^{p} \sum_{m=2}^{p} |f_{nm}|^2 (\lambda_n + \lambda_m)^{-\frac{1}{2}} \right),
\]

where, in the last inequality we have used Lemma 6.5 and Lemma 6.1. We have

**Lemma 6.5.** Let \(h \in \mathbb{P}^{p-1} \otimes \mathbb{P}^{p-1}\) be a polynomial expanded in terms of derivatives of discrete Dirichlet eigenvectors:

\[
h(y, z) = \sum_{n=2}^{p} f_{n1} \Phi_n'(y) \frac{1}{\sqrt{2}} + \sum_{m=2}^{p} f_{1m} \Phi_m'(z) + \sum_{n=2}^{p} \sum_{m=2}^{p} f_{nm} \Phi_n'(y) \Phi_m'(z).
\]

The following discrete norm is equivalent to the norm in the space \(\tilde{H}^{-\frac{1}{2}}(I^2)\) with equivalence constants independent of the polynomial degree \(p\):

\[
\| h \|^2 = \sum_{n=2}^{p} |f_{n1}|^2 \lambda_n^{-\frac{1}{2}} + \sum_{m=2}^{p} |f_{1m}|^2 \lambda_m^{-\frac{1}{2}} + \sum_{n=2}^{p} \sum_{m=2}^{p} |f_{nm}|^2 (\lambda_n + \lambda_m)^{-\frac{1}{2}}.
\]

**Proof.** The proof is based on the tensorization result,

\[
\tilde{H}^{-\frac{1}{2}}(I_y \times I_z) = L^2(I_y, \tilde{H}^{-\frac{1}{2}}(I_z)) + L^2(I_z, \tilde{H}^{-\frac{1}{2}}(I_y)).
\]

Lemma 6.3 implies that

\[
\| h \|^2_{L^2(I_y, \tilde{H}^{-\frac{1}{2}}(I_z))} \approx \sum_{n=2}^{p} |f_{n1}|^2 + \sum_{m=2}^{p} |f_{1m}|^2 \lambda_m^{-\frac{1}{2}} + \sum_{n=2}^{p} \sum_{m=2}^{p} |f_{nm}|^2 \lambda_m^{-\frac{1}{2}}
\]

\[
+ \sum_{n=2}^{p} \sum_{m=2}^{p} f_{nm} \frac{1}{\lambda_n + \lambda_m} (\beta_{nm}^\lambda)'(x) \frac{1}{\lambda_m^2} \Phi_n'(y) \Phi_m'(z).
\]
and
\[(6.33) \quad \|h\|^2_{L^2(f_\epsilon, H^{-1/2}(f_\epsilon))} \approx \sum_{n=2}^{p} |f_{n1}|^2 \lambda_n^{-1/2} + \sum_{m=2}^{p} |f_{1m}|^2 \lambda_m^{-1/2} + \sum_{n=2}^{p} \sum_{m=2}^{p} |f_{nm}|^2 \lambda_n^{-1/2}.\]

We have
\[(6.34) \quad \|h\|^2 \approx \sum_{n=2}^{p} |f_{n1}|^2 \min\{1, \lambda_n^{-1/2}\} + \sum_{m=2}^{p} |f_{1m}|^2 \min\{1, \lambda_m^{-1/2}\} + \sum_{n=2}^{p} \sum_{m=2}^{p} |f_{nm}|^2 \lambda_n^{-1/2},\]

which ends the proof. \(\square\)

In the same way we define the lift from face \(f_6\). Our final \(H(\text{div}, \Omega)\)-extension is defined by summing all face contributions,
\[(6.35) \quad H = H_1 + H_2 + H_3 + f_{4,11} H_{RT,4} + H_4 + H_5 + f_{6,11} H_{RT,6} + H_6,\]

where \(f_{4,11}\) and \(f_{6,11}\) are the average values of function \((6.26)\) over faces \(f_4, f_6\), and \(H_{RT,4}, H_{RT,6} \in V_1(\Omega)\) are the corresponding lowest-order Raviart-Thomas shape functions. We conclude with

**Theorem 6.6.** Operator \((6.35)\).

\[(6.36) \quad \mathcal{L}^{(p)}_n : V_p(\partial \Omega) \ni h \mapsto H \in V_p(\Omega),\]
defines a polynomial lift of normal traces. Its norm from \(H^{-1/2}(\partial \Omega)\) into \(H(\text{div}, \Omega)\) is bounded independently of the polynomial degree \(p\).

**Remark 6.7.** We can check that the lifting \(H\) is orthogonal to the curls of all fields with zero tangential trace \(E \in Q_{p,0}(\Omega)\). Moreover the divergence of \(H\) is constant. Conversely, if \(H \in V_p(\Omega)\) has these properties and a zero normal trace, it is zero. The proof uses similar arguments as previously. We deduce first that \(\text{div} H = 0.\) Therefore, there exists \(E \in Q_{p}(\Omega)\) such that \(\text{curl} E = H\). Since \(\gamma_n H = 0\), we deduce that \(\text{curl} \gamma_n E = 0\). Therefore there exists a surface potential \(u \in W_p(\partial \Omega)\) such that \(\nabla_{\partial \Omega} U = \gamma_n E\). Setting \(U = \mathcal{L}^{(p)}_0 u\), we obtain that \(\gamma_n \nabla U = \gamma_n E\). Finally \(H = \text{curl}(E - \nabla U)\) with \(E - \nabla U \in Q_{p,0}(\Omega)\). The orthogonality condition against the curls of \(Q_{p,0}(\Omega)\) gives \(H = 0\). \(\square\)

**7.** \(H(\text{curl})\) POLYNOMIAL EXTENSION OPERATOR IN 3D

Having constructed the polynomial extension operators for the spaces \(H^1(\Omega)\) and \(H(\text{div},\Omega)\), we proceed along exactly the same lines as for the continuous case discussed in Section 3.3. We consider the exact polynomial sequence \((2.10)\). Given a polynomial trace \(e_t \in Q_p(\partial \Omega)\), we compute its surface curl,
\[(7.1) \quad h = \text{curl}_{\partial \Omega} e_t\]

and use the \(H(\text{div})\)-extension operator \(\mathcal{L}^{(p)}_n\) to construct an \(H(\text{div},\Omega)\)-extension \(H\) of polynomial \(h\). We then use the Poincaré map to “take out the curl" out of
the data $e_t$ and conclude that the resulting function must be a surface gradient of a potential $u \in W_p(\partial \Omega)$ (with a zero average),
\begin{equation}
(7.2) \quad e_t - \gamma_t K H = \nabla_{\partial \Omega} u.
\end{equation}
The $H(\text{curl}, \Omega)$-extension is now obtained by summing the gradient of the $H^1(\Omega)$-extension of the potential $u$ with $KH$,
\begin{equation}
(7.3) \quad E = \nabla U + KH.
\end{equation}
Replicating the procedure from the continuous level is possible because the Poincaré map is polynomial preserving. We conclude our construction with

**Theorem 7.1.** Operator $(7.3)$,
\begin{equation}
(7.4) \quad \mathcal{L}^{(p)}_t : Q_p(\partial \Omega) \ni e_t \mapsto E \in Q_p,
\end{equation}
defines a polynomial lift of the tangential trace. Its norm from $H^{-\frac{1}{2}}(\text{curl}, \partial \Omega)$ into $H(\text{curl}, \Omega)$ is bounded independently of the polynomial degree $p$.

**Remark 7.2.** As in the continuous case, see Remark 4.3, we can get a canonical construction by replacing the Poincaré map $K$ by a $p$-depending operator $\tilde{K}$ defined as follows:
\begin{equation}
(7.5) \quad \tilde{K} H = KH + \nabla U_0 \quad \text{with} \quad U_0 \in W_{p,0}(\Omega) \quad \text{such that} \quad \|\tilde{K} H\|_{L^2(\Omega)} \quad \text{is minimal}.
\end{equation}
The operator norm of $\tilde{K}$ is not larger than the one of $K$, and the lift $\tilde{E}$ constructed in this way satisfies the orthogonality conditions
\begin{equation}
(7.6) \quad \int_{\Omega} \text{curl} \tilde{E} \cdot \text{curl} F = 0 \quad \forall F \in Q_{p,0}(\Omega) \quad \text{and} \quad \int_{\Omega} \tilde{E} \cdot \nabla V = 0 \quad \forall V \in W_{p,0}(\Omega).
\end{equation}
It is easy to see that these two orthogonality relations determine $\tilde{E}$ uniquely.

**Conclusions in 3D polynomial case.** With $p \geq 1$ any integer, the lift operators $\mathcal{L}^{(p)}_0$, $\mathcal{L}^{(p)}_t$ and $\mathcal{L}^{(p)}_n$ satisfy the following exact sequence and commuting diagram properties, reproducing those of the continuous case:
\begin{equation}
(7.7) \quad \begin{array}{c}
W_p(\Omega) \xrightarrow{\nabla} Q_p(\Omega) \xrightarrow{\text{curl}_{\partial \Omega}} V_p \xrightarrow{\text{div}} Y_p(\Omega) \\
\gamma_0 \downarrow L^{(p)}_0 \quad \gamma_t \downarrow L^{(p)}_t \quad \gamma_n \downarrow L^{(p)}_n \quad \gamma_{\text{avg}} \downarrow \mathcal{L}_{\text{avg}} \\
W_{p,0}(\partial \Omega) \xrightarrow{\nabla} Q_{p,0}(\partial \Omega) \xrightarrow{\text{curl}} V_{p,0}(\partial \Omega) \xrightarrow{\text{div}} Y_{p,0}(\partial \Omega) \xrightarrow{\gamma_{\text{avg}}} \mathbb{R}
\end{array}
\end{equation}
The operator $\mathcal{L}^{(p)}_0 : u \mapsto U$ is uniquely determined by the extra condition of orthogonality,
\begin{equation}
(7.8) \quad \int_{\Omega} \nabla U \cdot \nabla V = 0 \quad \forall V \in W_{p,0}(\Omega)
\end{equation}
and $\mathcal{L}^{(p)}_n : h \mapsto H$ by
\begin{equation}
(7.9) \quad \int_{\Omega} H \cdot \text{curl} E = 0 \quad \forall E \in Q_{p,0}(\Omega) \quad \text{and} \quad \text{div} H \in \mathbb{R}.
\end{equation}
The “canonical” version $\tilde{L}^{(p)}_t$ of the lift $e_t \mapsto \tilde{E}$ as defined in Remark 7.2 is uniquely determined by the orthogonality relations $(7.6)$. □
8. Conclusions

In the paper, we have constructed polynomial extension operators for a master hexahedron and the polynomial spaces forming the exact sequence corresponding to Nédélec’s hexahedron of the first type. The polynomial extension operators mimic closely the corresponding constructions on the continuous level based on separation of variables. In the presentation, we have restricted ourselves to the “isotropic” spaces (same polynomial order in each direction), but the whole procedure generalizes easily to the case of anisotropic spaces as well. Given a scalar space $P^{(p,q,r)}$, we arrange the element system of coordinates in such a way that $p \leq q \leq r$, and the construction presented in this paper goes through without any changes.

The existence of polynomial extension operators completes the theory of Projection-Based Interpolation; see [15, 13] for the hexahedral element. The obtained discrete $H^1(I^2)$ and $H^{-1/2}(I^2)$-norms may be used in the automatic $hp$-adaptivity algorithm presented in [12, 16].

Finally, we finish with a didactic comment on teaching the separation of variables. When presenting the solution of the Dirichlet problem for the Laplace equation on a square or cube, virtually all textbooks recommend splitting the data into edge or face contributions, and the solution of the corresponding single edge or face problems with pure Dirichlet conditions using the separation of variables. The superposition principle is then used to obtain the final solution. With a regular boundary data that guarantees the existence of a finite energy solution, the procedure breaks the solution into the corresponding edge or face solutions that, in general, have infinite energy. This can be avoided by using the mixed boundary conditions employed in this paper, which guarantee that all solutions corresponding to a nonhomogeneous single edge or face data remain of finite energy. The same comments apply to the Neumann problem.

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References


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