

# 1 Introduction

Our goal is to study the homogeneous magnetostatic problem on the exterior domain of a triangulated torus. That means that for the unbounded domain  $\Omega \subseteq \mathbb{R}^3$  we have  $\mathbb{R}^3 \setminus \Omega$  is a triangulated torus. We also need a piecewise straight (i.e. triangulated) closed curve around the torus. (TBD: Define the "triangulated torus" more rigorous)

Let  $B$  be a magnetic field on the domain  $\Omega$ . We then have the following boundary value problem:

$$\operatorname{curl} B = 0, \quad (1.0.1)$$

$$\operatorname{div} B = 0 \text{ in } \Omega \quad (1.0.2)$$

$$B \cdot n = 0 \text{ on } \partial\Omega \text{ and} \quad (1.0.3)$$

$$\int_{\gamma} B \cdot dl = C_0 \quad (1.0.4)$$

where  $n$  is the outward normal vector field on  $\partial\Omega$  and  $C_0 \in \mathbb{R}$ . We want to prove existence and uniqueness of solutions. In order to do so we will need to introduce Sobolev spaces of differential forms and basics from simplicial topology among other things...

## 2 Differential forms

### 2.1 Alternating maps

For the introduction of alternating maps we follow the short section in Arnold's book [2, Sec. 6.1.]. Let  $V$  be a real vector space with  $\dim V = n$ . Then  $k$ -linear maps are of the form

$$\omega : \underbrace{V \times V \times \dots \times V}_{k \text{ times}} \rightarrow \mathbb{R}$$

that are linear in every component. We call a  $k$ -linear form *alternating* if the sign switches when two arguments are exchanged i.e.

$$\omega(v_1, \dots, v_i, \dots, v_j, \dots, v_k) = -\omega(v_1, \dots, v_j, \dots, v_i, \dots, v_k), \text{ for } 1 \leq i < j \leq k, \quad v_1, \dots, v_k \in V.$$

This also means for any permutation  $\pi : \{1, 2, \dots, k\} \rightarrow \{1, 2, \dots, k\}$

$$\omega(v_{\pi(1)}, v_{\pi(2)}, \dots, v_{\pi(k)}) = \operatorname{sgn}(\pi) \omega(v_1, v_2, \dots, v_k)$$

Denote the space of alternating maps by  $\text{Alt}^k V$ .

For  $\omega \in \text{Alt}^k V$ ,  $\mu \in \text{Alt}^l V$  we define the wedge product  $\omega \wedge \mu \in \text{Alt}^{k+l} V$

$$(\omega \wedge \mu)(v_1, \dots, v_k, v_{k+1}, \dots, v_{k+l}) = \sum_{\pi} \text{sgn}(\pi) \omega(v_{\pi(1)}, \dots, v_{\pi(k)}) \mu(v_{\pi(k+1)}, \dots, v_{\pi(k+l)})$$

where we sum over all permutations  $\pi : \{1, \dots, k+l\} \rightarrow \{1, \dots, k+l\}$  s.t.  $\pi(1) < \dots < \pi(k)$  and  $\pi(k+1) < \dots < \pi(k+l)$ . This definition is not very intuitive. **TBD: Examples in 3D.**

For 1-forms i.e. linear functionals  $\omega_1, \dots, \omega_k$ ,  $k \leq n$  we have the formula ([3, p.260])

$$\omega_1 \wedge \dots \wedge \omega_k(v_1, \dots, v_k) = \det(\omega_s(v_t))_{1 \leq s, t \leq k}. \quad (2.1.1) \quad \{\text{eq:wedge\_product}\}$$

Let  $\{u_i\}_{i=1}^n$  be any basis of  $V$  and  $\{u^i\}_{i=1}^n$  the corresponding dual basis i.e.  $u^i \in V'$ ,  $u^i(u_j) = \delta_{ij}$  for  $i, j = 1, 2, \dots, n$ . Then

$$\{u^{i_1} \wedge u^{i_2} \wedge \dots \wedge u^{i_k} \mid 1 \leq i_1 < \dots < i_k \leq n\}$$

is a basis of  $\text{Alt}^k V$ . In particular,  $\dim \text{Alt}^k V = \binom{n}{k}$ .

Given an inner product  $\langle \cdot, \cdot \rangle_V$  on  $V$  we obtain an inner product on  $\text{Alt}^k V$  by defining

$$\langle u^{i_1} \wedge u^{i_2} \wedge \dots \wedge u^{i_k}, u^{j_1} \wedge \dots \wedge u^{j_k} \rangle_{\text{Alt}^k V} := \det[(\langle u_{i_k}, u_{i_l} \rangle_V)_{1 \leq k, l \leq n}]$$

which is then extended to all of  $\text{Alt}^k V$  by linearity. We denote with  $|\cdot|_{\text{Alt}^k V}$  the induced norm. For an orthonormal basis  $b_1, \dots, b_n$  the corresponding basis  $b^{i_1} \wedge b^{i_2} \wedge \dots \wedge b^{i_k}$ ,  $1 \leq i_1 < \dots < i_k \leq n$  is an orthonormal basis of  $\text{Alt}^k V$ .

We want to examine  $\text{Alt}^n V$  a bit closer. Take  $\omega \in \text{Alt}^n V$  arbitrary. First of all, we can recognize that if we have an ordered basis  $(u_1, \dots, u_n)$  and vectors  $(w_1, \dots, w_n)$  with transition matrix  $A$  i.e.  $w_i = \sum_j A_{j,i} u_j$  then

$$\begin{aligned} \omega(w_1, \dots, w_n) &= \sum_{k_1, \dots, k_n=1}^n \omega(u_{k_1}, u_{k_2}, \dots, u_{k_n}) \prod_{j=1}^n A_{k_j, j} \\ &= \omega(u_1, \dots, u_n) \sum_{\pi \text{ Permutation}} \text{sgn}(\pi) \prod_{j=1}^n A_{\pi(j), j} \\ &= \det(A) \omega(u_1, \dots, u_n). \end{aligned}$$

That also implies that the value on a ordered basis determines the alternating  $n$ -linear map completely.

$\text{Alt}^n V$  is one-dimensional and so we can choose a basis by fixing a specific non-zero element. We want to choose one that will be used later on.

We say that two bases of  $V$  have the same orientation if the change of basis has positive determinant. That divides the bases into two classes with different orientation. We choose one of these classes and call these bases positively oriented. In  $\mathbb{R}^n$ , the convention is to define the class as positively oriented which includes the standard orthonormal basis.

Let  $\{v_i\}_{i=1}^n$  be any positively oriented basis. Let  $M$  be the Gramian matrix i.e.  $M_{ij} = \langle v_i, v_j \rangle$  which is always a symmetric positive definite matrix. Then we define the *volume form*

$$\text{vol} := \sqrt{\det M} v^1 \wedge v^2 \wedge \dots \wedge v^n.$$

The claim is now that for any positively oriented orthonormal basis  $\{b_i\}_{i=1}^n$  we have

$$\text{vol}(b_1, b_2, \dots, b_n) = 1.$$

Let us denote the  $\tilde{v}_i = (\langle v_i, b_k \rangle)_{k=1}^n$  i.e. the coefficients of  $v_i$  in the orthonormal basis and  $\tilde{V} = (\tilde{v}_1 \mid \tilde{v}_2 \mid \dots \mid \tilde{v}_n)$  which is just the change of basis matrix. Then using basic linear algebra we get  $M = \tilde{V}^\top \tilde{V}$  and because both bases are positively oriented  $\sqrt{\det M} = \det \tilde{V}$ .

$$v^i(b_j) = v^i\left(\sum_{k=1}^n (\tilde{V}^{-1})_{kj} v_k\right) = (\tilde{V}^{-1})_{ij}.$$

So in total by using (2.1.1)

$$\text{vol}(b_1, b_2, \dots, b_n) = \det \tilde{V} \det(v^i(b_j))_{ij} = \det \tilde{V} \det \tilde{V}^{-1} = 1.$$

This property also defines the volume form uniquely so it is independent of the chosen basis. It also shows that  $\text{vol}$  is non-zero and thus

$$\text{Alt}^n V = \text{span}\{\text{vol}\}.$$

Of course, if we choose  $\{v_i\}_i$  to be an orthonormal basis to begin with the Gramian matrix is just the identity and  $\text{vol} = v^1 \wedge \dots \wedge v^n$ . Especially in the case of  $\mathbb{R}^n$  if we denote the standard dual basis by  $\{dx^i\}_{i=1}^n$  then

$$\text{vol} = dx^1 \wedge \dots \wedge dx^n.$$

Using the volume on  $V$  form we can now define the *Hodge star operator*  $\star : \text{Alt}^k V \rightarrow \text{Alt}^{n-k} V$  via the property

$$\omega \wedge \mu = \langle \star \omega, \mu \rangle_{\text{Alt}^{n-k} V} \text{vol} \quad \forall \omega \in \text{Alt}^k V, \mu \in \text{Alt}^{n-k} V.$$

The Hodge star is an isometry, we have  $\star\star = (-1)^{k(n-k)}\text{Id}$  and

$$\omega \wedge \star\mu = \langle \omega, \mu \rangle_{\text{Alt}^k V} \text{vol} \quad \forall \omega, \mu \in \text{Alt}^k V.$$

In particular in  $\mathbb{R}^3$ , we have  $\star\star = \text{Id}$  i.e.  $\star$  is self-inverse.

$\text{Alt}^0 V$  is just  $\mathbb{R}$  by definition. So the Hodge star now gives us a natural isomorphism from  $\text{Alt}^n V \rightarrow \mathbb{R}$ ,  $\star(\alpha \text{vol}) = \alpha$ . We call the real number that is associated with an element of  $\text{Alt}^n V$  *scalar proxy*. Similarly we have that  $\text{Alt}^1 V = V'$ , the usual dual space of  $V$ . Because  $V$  is finite-dimensional we know that  $V \cong V'$  using the Riesz representation. Then with the help of the Hodge star we obtain a natural isomorphism from  $\text{Alt}^{n-1} V \rightarrow V$ . We call the vector corresponding to a 1- or  $(n-1)$ -alternating map *vector proxy*.

Note that for  $n = 2$  the situation is slightly ambiguous, see [2, p.67]. But this case will not be relevant in this thesis.

Let us take a closer look at the case of  $V = \mathbb{R}^3$  with the standard basis vectors  $e_1, e_2$  and  $e_3$ . Denote the resulting elements of the dual basis with  $dx^i$ . Then for some  $v \in V$  we get the corresponding 1-alternating map  $v_1 dx^1 + v_2 dx^2 + v_3 dx^3 \in \text{Alt}^1$  and the alternating bilinear map  $v_1 dx^2 \wedge dx^3 - v_2 dx^1 \wedge dx^3 + v_3 dx^1 \wedge dx^2 \in \text{Alt}^2$ . For the scalar proxies, take  $c \in \mathbb{R}$ . Then  $c \in \text{Alt}^0$  of course and because we have  $\text{vol} = dx^1 \wedge dx^2 \wedge dx^3$  we get the corresponding  $c dx^1 \wedge dx^2 \wedge dx^3 \in \text{Alt}^3$ .

We can now use this relation to investigate the meaning of the wedge product for vector proxies. Let us denote  $\Phi^k$  as the isomorphism to the  $k$ -alternating map with this scalar or vector as proxy. Let  $v, w \in \mathbb{R}^3$ . Then

$$\begin{aligned} \Phi^1 v \wedge \Phi^1 w &= \Phi^2(v \times w) \text{ and} \\ \Phi^1 v \wedge \Phi^2 w &= \Phi^3(v \cdot w). \end{aligned}$$

Note that for a 0-alternating map (i.e. a scalar) the wedge product is nothing but the usual multiplication. So in 3 dimensions, we can always relate the operations of alternating maps forms to the operations of the corresponding proxies.

## 2.2 Differential forms

Before we define differential forms, let us start by revising some basics from differential geometry. We follow the approach from [3, Sec. II.5]. It should be noted that there are different definitions of tangent space, but these lead to isomorphic notions (see e.g. [4, Sec.1.B]). Let  $M$  be an  $n$ -dimensional smooth manifold with or without boundary. For a point  $p \in M$  and a neighborhood  $U$  we call a function  $f : U \rightarrow \mathbb{R}$  differentiable at  $p$  if for a local chart  $\phi : U \rightarrow \mathbb{R}^k$  we have that  $f \circ \phi^{-1}$  is differentiable at  $\phi(p)$ .

This definition is independent of the chart. Let  $(V, \psi)$  with  $p \in V$  be another chart. Then  $f \circ \psi^{-1} = f \circ \phi^{-1} \circ \phi \circ \psi^{-1}$  and because  $\phi \circ \psi^{-1}$  is a diffeomorphism it is differentiable as well.

These type of definitions via local charts on a manifold are frequent in differential geometry. This is a proper definition if it is independent of the chosen chart. Because we do not want to bother with the technicalities of differential geometry too much we will very often leave out these types of proofs.

Let  $I \subseteq \mathbb{R}$  be an interval containing 0 and  $\gamma : I \rightarrow M$  be a differentiable curve with  $\gamma(0) = p \in M$ . For a differentiable  $f : U \rightarrow \mathbb{R}$  we define the directional derivative  $D_\gamma(f) := \frac{d}{dt}f(\gamma(t))|_{t=0}$ . We call the functional  $D_\gamma : C^1(U) \rightarrow \mathbb{R}$  tangent vector.

We define

$$\frac{\partial f}{\partial x_i}(p) = \frac{\partial(f \circ \phi^{-1})}{\partial x_i}(\phi(p)). \quad (2.2.1) \quad \{\text{eq:derivative\_o}\}$$

Let us emphasize that this value is obviously not independent of the chosen chart.

We can now express a tangent vector  $D_\gamma$  by

$$D_\gamma(f) = \frac{d}{dt}f(\gamma(t))|_{t=0} = \frac{d}{dt}(f \circ \phi^{-1} \circ \phi)(\gamma(t))|_{t=0} \quad (2.2.2)$$

$$= \sum_{i=1}^k \frac{\partial(f \circ \phi^{-1})}{\partial x_i}(\phi(p)) (\phi_i \circ \gamma)'(0) = \left( \sum_{i=1}^k v_i \frac{\partial}{\partial x_i} \Big|_p \right) (f). \quad (2.2.3)$$

Thus we can express

$$D_\gamma = \sum_{i=1}^k (\phi_i \circ \gamma)'(0) \frac{\partial}{\partial x_i} \Big|_p.$$

So we have that

$$T_p M = \text{span} \left\{ \frac{\partial}{\partial x_i} \Big|_p \right\}_{i=1}^n.$$

We will show that this indeed a basis. Assume we have  $\sum_{i=1}^n \lambda_i \frac{\partial}{\partial x_i} \Big|_p = 0$ . Then because  $\phi_j \circ \phi^{-1}(x) = x_j$  for  $x \in \phi(U)$  and  $1 \leq j \leq n$ . Then we have

$$0 = \left( \sum_{i=1}^n \lambda_i \frac{\partial}{\partial x_i} \Big|_p \right) (\phi_j) = \sum_{i=1}^n \lambda_i \frac{\partial x_j}{\partial x_i}(\phi(p)) = \lambda_j$$

so  $\frac{\partial}{\partial x_i} \Big|_p$  are linearly independent and thus a basis of  $T_p M$ .

**Definition 2.2.1** (Differential forms). A differential  $k$ -form  $\omega$  is a maps any point  $p \in M$  to a alternating  $k$ -linear mapping  $\omega_p \in \text{Alt}^k T_p M$ . We denote the space of differential  $k$ -forms on  $M$  as  $\Lambda^k M$ .

Let  $T_p^* M$  be the dual space of  $T_p M$  which is usually called *cotangent space*. As before let us choose a local chart  $\phi : U \rightarrow \mathbb{R}^n$  with  $p \in U$  and define  $\frac{\partial}{\partial x_i}|_p$  as before. Because we know that this is a basis of  $T_p M$  we denote the corresponding dual basis as  $dx^i$ ,  $i = 1, \dots, n$ . From the consideration about alternating maps from section ?? we can now write any  $\omega \in \Lambda^k M$  with

$$\omega_p = \sum_{1 \leq i_1 < \dots < i_k \leq n} a_{i_1, \dots, i_k}(p) dx^{i_1} \wedge dx^{i_2} \wedge \dots \wedge dx^{i_k}$$

with  $a_{i_1, \dots, i_k}(p) \in \mathbb{R}$ . The regularity of differential forms is then defined via the regularity of these coefficients i.e. we call a differential form smooth if all the  $a_{i_1, \dots, i_k}$  are smooth and we call a differential form differentiable if all the  $a_{i_1, \dots, i_k}$  are differentiable and so on. We denote the space  $C^\infty \Lambda^k M$  the space of smooth differential  $k$ -forms and analogous for other regularity.

$C_0^\infty \Lambda^k(M)$  are the smooth compactly supported differential forms which will become very crucial later when we discuss Sobolev spaces of differential forms (see Sec. ??). Note that the support is not defined via the coefficient functions as above, but directly on the manifold i.e.  $\text{supp } \omega = \overline{\{p \in M \mid \omega_p \neq 0\}} \subseteq \text{int } M$  where the closure and the interior are w.r.t. the topology on  $M$ .

In order to define the Hodge star and an inner product on differential forms we need that  $T_p M$  is an inner product space.

A Riemannian metric gives us at every point  $p \in M$  a symmetric, positive definite bilinear form  $g_p : T_p M \times T_p M \rightarrow \mathbb{R}$ . Additionally, a Riemannian metric is assumed to be smooth in the sense that for smooth vector fields  $X$  and  $Y$  we have  $p \mapsto g_p(X, Y)$  is a smooth function. The degree of smoothness depends on the smoothness of the manifold. **More details...** Manifolds on which a Riemannian metric is defined are called *Riemannian manifolds*. The Riemannian metric provides us with the inner product on every tangent space  $T_p M$ .

Now we will move on to differential forms on a smooth, oriented, Riemannian manifold  $M$  of dimension  $n$  with or without boundary. We denote the Riemannian metric by  $g$ . Let  $p \in M$  and  $T_p M$  be the tangent space at the point  $p$ . Due to our assumptions on  $M$ , this is an inner product space of dimension  $n$  and we can apply all of the constructions from the previous chapter **Check this!**. We have a volume form  $\text{vol}$  on  $M$  so the previous constructions using the Hodge star operator are well-defined. [4, p. 2.7].

Let  $\{(U_i, \phi_i)\}_{i=1}^\infty$  be an oriented atlas of  $M$ . For  $p \in U_i$  we can define using local coordinates

$$g_{kl}^{(i)}(p) := g_p\left(\frac{\partial}{\partial x_k^{(i)}}\Big|_p, \frac{\partial}{\partial x_l^{(i)}}\Big|_p\right)$$

where we use the superscript  $^{(i)}$  to mean the local coordinates for chart  $\phi_i$ . Then we define the matrix  $G^{(i)} := (g_{kl}^{(i)})_{k,l} \in \mathbb{R}^{n \times n}$  which is just the resulting Gramian matrix. Then we obtain the volume form

$$\text{vol}_p = \det G^{(i)} dx_{(i)}^1 \wedge dx_{(i)}^2 \wedge \dots \wedge dx_{(i)}^n$$

where  $dx_{(i)}^k$  are the dual basis corresponding to  $\partial/\partial x_k^{(i)}$  the local coordinates of chart  $\phi_i$ .

We know that this works if we choose any positively oriented basis. Because our manifold is orientable and we chose a oriented atlas  $(U_i, \phi_i)$  we get that if we choose a different chart  $(U_j, \phi_j)$  then the corresponding basis of the tangent space  $\{\frac{\partial}{\partial x_{(j)}^k}\}_k$  is also positively oriented because the change of basis matrix  $D(\phi_j \circ \phi_i^{-1})(\phi(p))$  has positive determinant.

We define the Hodge star operator to differential forms  $\star : \Lambda^k(\Omega) \rightarrow \Lambda^{n-k}(\Omega)$  simply by applying it pointwise. In order for the Hodge star to be well-defined the assumption of an orientation on our manifold is crucial. We do the same for the exterior product to get  $\wedge : \Lambda^k \times \Lambda^l \rightarrow \Lambda^{k+l}$ .

Let  $\omega \in \Lambda^k(M)$  be given in local coordinates with some chart  $(U, \phi)$  s.t.  $p \in U$  as above,

$$\omega_p = \sum_{1 \leq i_1 < \dots < i_k \leq n} a_{i_1, \dots, i_k}(p) dx^{i_1} \wedge dx^{i_2} \wedge \dots \wedge dx^{i_k}$$

Then we define the exterior derivative  $d : \Lambda^k(M) \rightarrow \Lambda^{k+1}(M)$ . By

$$(d\omega)_p = \sum_{1 \leq i_1 < \dots < i_k \leq n} \sum_{i=1}^n \frac{\partial a_{i_1, \dots, i_k}}{\partial x_i}(p) dx^i \wedge dx^{i_1} \wedge dx^{i_2} \wedge \dots \wedge dx^{i_k}$$

We remind of the that the derivative of  $a_{i_1, \dots, i_k}$  is meant w.r.t. the chart as defined at (2.2.1). It can be shown that the  $d\omega$  is independent of the chosen chart.

If the manifold is oriented and we have thus a Hodge star operator. Then we define the *codifferential operator*  $\delta := (-1)^{n(k-1)+1} \star d \star$  which is then an operator  $\Lambda^k(M) \rightarrow \Lambda^{k-1}(M)$ .

The exterior derivative and the codifferential both require the differential form to be differentiable. Later we will extend this in weak sense so classical differentiability is no longer required (see ??).

Let us have a closer look at this in the simplest situation of  $M$  being a domain  $U \subseteq \mathbb{R}^3$ . Let  $\rho \in C^1(U)$  be a scalar and  $F \in C^1(U; \mathbb{R}^3)$  be a vector field. Then we can view  $\rho$  as a 0-form  $\rho \in C^1 \Lambda^0 U$ . In this case, we can simply take the identity as a chart and  $g_x(\partial/\partial x_i, \partial/\partial x_j) = \delta_{ij}$ . Then we obtain

$$(d\rho)_x = \sum_{i=1}^3 \frac{\partial \rho}{\partial x_i} dx^i.$$

Because  $\partial/\partial x_i$  are orthonormal using the Riesz isomorphism we can identify  $d\rho$  with the vector field

$$\sum_{i=1}^3 \frac{\partial \rho}{\partial x_i} \frac{\partial}{\partial x_i} \leftrightarrow \text{grad } \rho.$$

So the exterior derivative of zero forms corresponds to the gradient. In an analogous way using vector proxies one can show that for 1-forms it corresponds to the curl and for 2-forms to the divergence. This also shows the usefulness of the exterior derivative because it provides a way to unify these differential operators and generalize them to smooth manifolds.

## 2.3 Sobolev spaces of differential forms

In order to rigorously define Sobolev spaces we have to define  $L^p$ -spaces of differential forms first. But before we can do that we should have a look how integration of a function can be defined on a smooth orientable Riemannian manifold  $M$ .

We want to define integration in the framework of usual measure and integration theory which means defining it as a Lebesgue integral w.r.t. a measure on  $M$  which we have to define first along with a  $\sigma$ -algebra on  $M$ .

It is well known that the borel  $\sigma$ -algebra  $\mathcal{B}$  on  $\mathbb{R}^n$  is generated by all open sets. This idea can be applied to any topological space  $X$  by defining the borel  $\sigma$ -algebra  $\mathcal{B}(X)$  as the  $\sigma$ -algebra generated by all open sets. So we can simply use the topology on  $M$  to define our  $\sigma$ -algebra  $\mathcal{B}(M)$ . Because we know that all our charts  $\phi_i : U_i \rightarrow \mathbb{R}^n$  are homeomorphisms it is very straightforward to show that a set  $E \in \mathcal{B}(M)$  i.i.f.  $\phi_i(E \cap U_i)$  is Borel-measurable.

Now, we need to define a measure on the manifold. This measure will also involve the charts and it requires the manifold to be Riemannian and orientable. Let  $\{\chi_i\}_{i=1}^\infty$  be partition of unity subordinate to the  $U_i$ . **I need stronger requirements for the manifold. We need a countable basis. Or does any Riemannian orientable manifold have that?** Then we define the



Riemannian measure for any  $E \in \mathcal{B}(M)$

$$V(E) := \sum_{i=1}^{\infty} \int_{\phi_i(U_i)} \chi_i(\phi_i^{-1}(x)) \sqrt{\det G^{(i)}(\phi_i^{-1}(x))} dx \in [0, \infty]$$

It can be shown that it is independent of the chosen oriented atlas using the transformation behaviour of  $G^{(i)}$ . But the orientation is crucial for it to be well-defined.

Now that we have the measure space  $(M, \mathcal{B}(M), V)$  we can define integration in the usual Lebesgue way. It is easily shown that a function  $f : M \rightarrow \mathbb{R}$  is measurable i.i.f.  $f \circ \phi_i^{-1}$  is measurable for every chart  $\phi_i$ . It is then simply an application of the definition of Lebesgue integration to show that for any measurable  $f \geq 0$  we can express the integration as

$$\int_M f dV = \sum_{i=1}^{\infty} \int_{\phi_i(U_i)} \chi_i(\phi_i^{-1}(x)) f(\phi_i^{-1}(x)) \sqrt{\det G^{(i)}(\phi_i^{-1}(x))} dx.$$

By introducing the integral as a Lebesgue integral w.r.t. the Riemannian measure we inherit the theoretical framework of Lebesgue integration. For example, we know that the spaces  $L^p(M, V)$  for  $1 \leq p < \infty$ , i.e. the  $p$ -integrable real-valued functions w.r.t. the Riemannian measure, are Banach spaces.

### 2.3.1 Integration of differential forms

Once again, we should first ask ourselves what a measurable differential form should be. We know that we can express our differential form locally for  $p \in U_i$  using the local coordinates as

$$\omega_p = \sum_{1 \leq i_1 < \dots < i_k \leq n} a_{i_1, \dots, i_k}(p) dx^{i_1} \wedge dx^{i_2} \wedge \dots \wedge dx^{i_k}.$$

In the spirit of the above steps we call a  $\omega \in \Lambda^k(M)$  measurable if for every chart  $\phi_i$  the coefficient functions are measurable. This is once again independent of the chosen atlas. This can be proven by identifying  $\omega$  as a section of the vector bundle of  $k$ -linear alternating maps over  $M$ . We did not define vector bundles however and will skip the proof. For now assume our manifold to be smooth and orientable, but not necessarily Riemannian.

Next, we will define integration of an  $n$ -form over an  $n$  dimensional manifold. At first, we do so for an open set  $U \subseteq \mathbb{R}^n$ . This is the simplest example of an  $n$ -dimensional manifold where we only have one chart which is the

identify and the local coordinates are just our standard coordinates. Let  $\omega$  be a measurable  $n$ -form on  $U$  so we can write

$$\omega_x = f(x)dx_1 \wedge dx_2 \wedge \dots \wedge dx_n$$

for  $x \in U$  with  $f : U \rightarrow \mathbb{R}$  being measurable. We can now simply define

$$\int_U \omega = \int_U f(x)dx.$$

With this definition at hand we can now extend this definition to any smooth oriented  $n$ -dimensional manifold  $M$ . As it is often done in differential geometry we will work locally first and then extend this construction globally by using a partition of unity.

Let  $(U, \phi)$  be a chart on  $M$  and assume  $\text{supp } \omega \subseteq U$ . Then  $(\phi^{-1})^* \omega$  **Define the pullback** is a  $n$ -form on  $\phi(U) \subseteq \mathbb{R}^n$  and we can apply our prior definition. So now we just define

$$\int_M \omega := \int_{\phi(U)} (\phi^{-1})^* \omega.$$

Once again, it can be shown that this definition does not depend on the chart if we choose the atlas corresponding to the orientation of the manifold.

Now let us move on to the global definition. Let  $\{(U_i, \phi_i)\}_{i=1}^\infty$  be an oriented atlas and let  $\{\chi_i\}_{i=1}^\infty$  be a partition of unity subordinate to it. Then  $\text{supp } \chi_i \omega \subseteq U_i$  and we define

$$\int_M \omega := \sum_{i=1}^\infty \int_M \chi_i \omega.$$

This definition is also independent of the chosen chart and partition of unity. We will omit the proof.

We will now have a look how the integration of functions and of differential forms are related to each other. We know that for  $p \in U_i$  we can write the volume form as

$$\text{vol}_p = \sqrt{\det G^{(i)}(p)} dx_{(i)}^1 \wedge dx_{(i)}^2 \wedge \dots \wedge dx_{(i)}^n.$$

Because  $(\phi_i^{-1})^* dx_{(i)}^k = dx^k$  i.e. the standard dual basis in  $\mathbb{R}^n$  we have

$$((\phi_i^{-1})^* \text{vol})_x = \sqrt{\det G^{(i)}(\phi_i^{-1}(x))} dx^1 \wedge dx^2 \wedge \dots \wedge dx^n.$$

That means for a  $n$ -form  $f \text{ vol}$  we can write the integral as

$$\int_M f \text{ vol} = \sum_{i=1}^{\infty} \int_{\phi_i(U_i)} \chi_i(\phi_i^{-1}(x)) f(\phi_i^{-1}(x)) \sqrt{\det G^{(i)}(\phi_i^{-1}(x))} dx^1 \wedge \dots \wedge dx^n$$

and we see

$$\int_M f dV = \int_M f \text{ vol}$$

with the two different notions of integration. So we see that the two definitions are essentially equivalent. The big advantage of considering these two approaches is that we know the integration of differential forms is within the framework of Lebesgue integration. It is then also clear how integrability for  $n$ -forms should be defined. We call an  $n$ -form  $f \text{ vol}$  integrable if  $f$  is integrable w.r.t. the Riemannian measure.

### 2.3.2 Stokes' theorem and integration by parts

One of the most important results about the integration of differential forms is Stokes' theorem which we will state in this section. From it, we will obtain a integration by parts formula.

But before we do so we have to check how to define the restriction of a differential form to a submanifold  $N \subseteq M$ . We have the inclusion  $\iota : N \hookrightarrow M$ . Then for a smooth differential form  $\omega \in C^\infty \Lambda^k(M)$  we define the restriction just via the pullback of the inclusion operator i.e.  $\iota^* \omega \in C^\infty \Lambda^k(N)$ .

For a  $k$ -dimensional submanifold  $N$  we then denote the integration of an  $k$ -form  $\omega$  as

$$\int_N \iota^* \omega = \int_N \omega.$$

**Theorem 2.3.1** (Stokes). *Let  $M$  be a smooth oriented manifold with boundary  $\partial M$ . Let  $\omega$  be a smooth compactly supported  $(n-1)$ -form. Then we have*

$$\int_M d\omega = \int_{\partial M} \omega.$$

This theorem gives us a relation of the boundary and the exterior derivative which will be crucial in the topological context of differential forms. We will investigate this in the section about homology (see Sec. ??).

We can also derive a form of the integration by parts formula from it. Let  $\omega \in C_0^1 \Lambda^k(M)$  and  $\mu \in C_0^1 \Lambda^{n-k-1}(M)$ . Then  $\omega \wedge \mu \in C_0^1 \Lambda^{n-1}(M)$  and we have from the Leibniz formula ??

$$d(\omega \wedge \mu) = d\omega \wedge \mu + (-1)^k \omega \wedge d\mu.$$

By integrating both sides over  $M$  and applying Stokes' theorem we obtain

$$\int_{\partial M} \omega \wedge \mu = \int_M d\omega \wedge \mu + (-1)^k \int_M \omega \wedge d\mu.$$

Using the codifferential  $\delta$  and the Hodge star operator together with the alternative expression of the Leibniz rule ?? we can obtain for  $\nu \in C_0^1 \Lambda^{k+1}(M)$

$$\int_M d\omega \wedge \star \nu = \int_M \omega \wedge \star \delta \nu + \int_{\partial M} \omega \wedge \star \nu.$$

This integration by parts will be used in the next section to extend the exterior derivative in the weak sense in analogy to the usual introduction of the weak derivative,

### 2.3.3 Sobolev spaces of differential forms

Then we define the  $L_p$ -norm of a  $k$ -form  $\omega$  for  $1 \leq p < \infty$  as (cf. [5])

$$\|\omega\|_{L_p^k(\Omega)} := \left( \int_{\Omega} \|\omega_x\|_{\text{Alt}^k T_x M}^p dV(x) \right)^{1/p}.$$

$L_p^k(\Omega)$  are the spaces of  $k$ -forms s.t. the corresponding  $L_p$ -norm is finite. For  $p = 2$  we obtain a Hilbert space (cf. [2, Sec. 6.2.6]) with the  $L_2$  inner product

$$\langle \omega, \nu \rangle := \int_{\Omega} \langle \omega_x, \nu_x \rangle_{\text{Alt}^k T_x M} dx = \int_{\Omega} \omega \wedge \star \nu \quad (2.3.1) \quad \{\text{eq: def\_inner\_pr}\}$$

**Proposition 2.3.2.** *The Hodge star operator  $\star : L_2^k(\Omega) \rightarrow L_2^{n-k}(\Omega)$  is a Hilbert space isometry.*

*Proof.* This follows directly from the definition of the inner product (2.3.1) and the fact that  $\star$  is an isometry when applied to alternating forms  $\text{Alt}^k T_x M$ .  $\square$

Our next goal is to extend the exterior derivative  $d$  of smooth differential forms in the weak sense (cf. [5]). Let  $\mathring{d} : L_2^k(\Omega) \rightarrow L_2^{k+1}(\Omega)$  be the exterior derivative as an unbounded operator with domain  $D(\mathring{d}) = C_0^\infty \Lambda^k(\Omega)$  which

are the smooth compactly supported differential forms  $\varphi$  of degree  $k$  with  $\text{supp } \varphi \subseteq \text{int } M$ .

Note that when we talk about smoothness or regularity of differential forms we always mean the regularity of the coefficients when the form is expressed via local charts.

Analogous, let  $\delta : L_2^k(\Omega) \rightarrow L_2^{k-1}(\Omega)$  be the codifferential operator  $\delta := (-1)^{n(k-1)+1} \star d \star$  also with domain  $C_0^\infty \Lambda^k(\Omega)$ .

Then the exterior derivative  $d\omega \in L_p^{k+1}(\Omega)$  is defined as the unique  $(k+1)$ -form in  $L_p^{k+1}(\Omega)$  s.t.

$$\int_{\Omega} d\omega \wedge \star \phi = \int_{\Omega} \omega \wedge \star \delta \phi \quad \forall \phi \in C_0^\infty \Lambda^k(\Omega).$$

Just as in the usual Sobolev setting we define the following spaces:

$$\begin{aligned} W_p^k(\Omega) &= \{ \omega \in L_p^k(\Omega) \mid d\omega \in L_p^{k+1}(\Omega) \}, \\ W_{p,loc}^k(\Omega) &= \{ \omega \text{ } k\text{-form} \mid \omega|_A \in W_p^k(A) \text{ for every open } A \subseteq \Omega \text{ s.t. } \overline{A} \subseteq \Omega \text{ is compact} \}. \end{aligned}$$

For  $\omega \in W_p^k(\Omega)$  for  $p < \infty$  we define the norm

$$\|\omega\|_{W_p^k(\Omega)} := \left( \|\omega\|_{L_p^k(\Omega)}^p + \|d\omega\|_{L_p^{k+1}(\Omega)}^p \right)^{1/p}.$$

**Remark 2.3.3.** Throughout this thesis, we will mostly deal with open subdomains  $\Omega \subseteq \mathbb{R}^n$  with Lipschitz boundary. Then  $\Omega$  is a smooth submanifold of  $\mathbb{R}^n$  and  $\overline{\Omega}$  is a Lipschitz manifold with boundary. If we now assume that  $\Omega = \text{int } \overline{\Omega}$  then  $W_p^k(\Omega)$  and  $W_p^k(\overline{\Omega})$  are essentially the same. Take  $\omega \in W_p^k(\Omega)$  and extend it arbitrarily to  $\overline{\omega} \in W_p^k(\overline{\Omega})$ . Then because  $\partial\Omega$  is a null set  $\overline{\omega} \in L_2^k(\overline{\Omega})$  and because the definition of the exterior derivative uses only smooth functions with compact support contained in  $\text{int } \overline{\Omega} = \Omega$  we get that  $d\overline{\omega} = d\omega \in L_2^k(\overline{\Omega})$  (again by choosing arbitrary values on the boundary). From now on we will in the assumed setting treat the spaces  $W_p^k(\overline{\Omega})$  and  $W_p^k(\Omega)$  as the same.

**Definition 2.3.4** ( $L^p$ -cohomology). We define the following subspaces of  $W_p^k(\Omega)$ ,  $1 \leq p \leq \infty$ :

$$\begin{aligned} \mathfrak{B}_k &:= dW_p^{k-1}(\Omega) \text{ and} \\ \mathfrak{Z}_k &:= \{ \omega \in W_p^k(\Omega) \mid d\omega = 0 \}. \end{aligned}$$

We call the  $k$ -forms in  $\mathfrak{B}_k$  exact and the forms in  $\mathfrak{Z}_k$  closed. Because  $d \circ d = 0$  we always have  $\mathfrak{B}_k \subseteq \mathfrak{Z}_k$ . Then we define the de Rham- or  $L^p$ -cohomology space  $H_{p,dR}^k(\Omega)$  as the quotient space

$$H_{p,dR}^k(\Omega) := \mathfrak{Z}_k / \mathfrak{B}_k.$$

We want to examine the Hilbert space  $L_2^k(\Omega)$  more closely (see [2, Sec. 6.2.6] for more details). We denote  $H^k(d; \Omega) := W_2^k(\Omega)$ . If the domain is clear we will leave it out. Note that the above definition of the exterior derivative is in the Hilbert space setting equivalent to defining  $d$  as the adjoint of  $\mathring{\delta}$ .

In order to extend  $\mathring{\delta}$  as well, we will need the following

**Definition 2.3.5** (Codifferential operator). Analogous to the smooth case, we define the *codifferential operator* for any  $k$  as an unbounded operator  $\delta : L_2^k(\Omega) \rightarrow L_2^{k-1}$  as

$$\delta := (-1)^{n(k-1)+1} \star d \star$$

with domain

$$D(\delta) = \{\omega \in L_2^k(\Omega) \mid \star \omega \in H^{n-k}(d)\} =: H^k(\delta; \Omega).$$

**Proposition 2.3.6.**  $\delta = \mathring{d}^*$  i.e.  $\delta$  is the adjoint of  $\mathring{d}$ .

*Proof.* Denote with  $D(\mathring{d}^*) \subseteq L_2^{k-1}(\Omega)$  the domain of the adjoint. Now take  $\omega \in H^k(\delta)$  and  $\phi \in C_0^\infty \Lambda^k(\Omega)$ . Then

$$\begin{aligned} \langle \delta \omega, \phi \rangle &= (-1)^{nk+1} \langle \star d \star \omega, \phi \rangle \\ &= (-1)^{nk+1} (-1)^{k(n-k)} \langle d \star \omega, \star \phi \rangle = (-1)^{nk+1} (-1)^{k(n-k)} \langle \star \omega, \mathring{\delta} \star \phi \rangle \\ &= (-1)^{nk+1} (-1)^{k(n-k)} (-1)^{n(n-k-1)+1} \langle \star \omega, \star \mathring{d} \star \star \phi \rangle \\ &= (-1)^{n(n-1)+2} (-1)^{k(n-k)} \langle \omega, \mathring{d} \star \star \phi \rangle \\ &= \langle \omega, \mathring{d} \phi \rangle \end{aligned}$$

where we used repeatedly that  $\star$  is an isometry and  $\star \star = (-1)^{k(n-k)} \text{Id}$ . This shows that  $H^{k+1}(\delta) \subseteq D(\mathring{d}^*)$  and that  $\mathring{d}^* \omega = \delta \omega$ . Now for the other inclusion assume that  $\omega \in D(\mathring{d}^*)$  and take  $\phi \in C_0^\infty \Lambda^{n-k}(\Omega)$  arbitrary.

$$\langle \star \omega, \mathring{\delta} \phi \rangle = \pm \langle \omega, \mathring{d} \star \phi \rangle = \pm \langle \mathring{d}^* \omega, \star \phi \rangle = \pm \langle \star \mathring{d}^* \omega, \phi \rangle.$$

Here we use  $\pm$  to mean that we choose the sign correctly, s.t. all the operations are correct. Then by choosing the sign appropriately we find that  $\pm \star \mathring{d}^* \omega = d \star \omega$  and therefore  $\star \omega \in H^{n-k-1}(d)$  so we proved  $D(\mathring{d}^*) \subseteq H^{k+1}(\delta)$  and we are done.  $\square$

In order to deal with the boundary of our domain we introduce Homogeneous boundary conditions for these Sobolev spaces of differential forms.

{def:zero\_boundar

**Definition 2.3.7** (Zero boundary condition). We say that  $\omega \in H^k(d; \Omega)$  has zero boundary condition if

$$\langle d\omega, \chi \rangle_{L_2^{k+1}(\Omega)} = \langle \omega, \delta\chi \rangle_{L_2^k(\Omega)} \quad \forall \chi \in H^{k+1}(\delta; \Omega).$$

Denote  $\mathring{H}^k(d; \Omega) := \{\omega \in H^k(d; \Omega) \mid \omega \text{ has zero boundary condition}\}.$

Of course we should justify why this is a reasonable definition. If  $\Omega$  is lipschitz and bounded we have the integration by parts formula (cf. [2, Thm. 6.3])

$$\int_{\Omega} d\omega \wedge \mu = (-1)^k \int_{\Omega} \omega \wedge d\mu + \int_{\partial\Omega} \text{tr } \mu \wedge \text{tr } \omega \quad \text{for } \omega \in H^1\Lambda^k(\Omega), \mu \in H^{n-k-1}(d; \Omega)$$

where  $H^1\Lambda^k(\Omega)$  are the differential forms with all coefficients being in  $H^1(\Omega)$  (here we mean just the standard Sobolev space). Let now  $\omega \in \mathring{H}^k(d)$ . Then if we use the integration by parts formula and  $\langle d\omega, \mu \rangle_{L^{k+1}(\Omega)} = \langle \omega, \delta\mu \rangle_{L^k(\Omega)}$  we get after some computation using the Hodge star

$$\langle \text{tr } \omega, \star \text{tr } \star \mu \rangle_{L^k(\Omega)} = 0 \quad \forall \mu \in H^1\Lambda^k(\Omega).$$

The trace operator  $\text{tr} : H^1\Lambda^k(\Omega) \rightarrow H^{1/2}\Lambda^k(\Omega)$  is surjective [2, Thm. 6.1].

$$\star \text{tr } \star H^1\Lambda^{k+1}(\Omega) = \star \text{tr } H^1\Lambda^{n-k-1}(\Omega) = \star H^{1/2}\Lambda^{n-k-1}(\Omega) = H^{1/2}\Lambda^k(\Omega)$$

is dense in  $L_2^k(\Omega)$ . Thus  $\text{tr } \omega = 0$ . So in the case of bounded Lipschitz domains this definition is reasonable. The reason why we chose to define it as in Def. 2.3.7 is that is easily extendible to unbounded domains and the regularity of the boundary is not an issue.

Then we define the spaces

$$H_0^k(d; \Omega) := \{\omega \in H^k(d; \Omega) \mid d\omega = 0\}$$

$$\mathring{H}_0^k(d; \Omega) := \{\omega \in \mathring{H}^k(d; \Omega) \mid d\omega = 0\}$$

i.e. the spaces of closed forms. We will use the analogous definition for  $H_0^k(\delta; \Omega)$  and  $\mathring{H}_0^k(\delta; \Omega)$  which we call coclosed forms. We then define the spaces of harmonic forms

$$\mathring{H}_0^k(d, \delta; \Omega) := \{\omega \in \mathring{H}^k(d; \Omega) \mid d\omega = 0, \delta\omega = 0\}.$$

With this one can prove the Hodge decomposition ([2, Lemma 1])

$$L_2^k(\Omega) = \overline{d\mathring{H}^{k-1}(d)} \overset{\perp}{\oplus} \mathring{H}_0^k(d, \delta) \overset{\perp}{\oplus} \overline{\delta H^{k+1}(\delta)} \quad (2.3.2) \quad \{\text{hodge\_decomposi}$$

and furthermore for the closed and coclosed forms respectively,

$$\mathring{H}_0^k(d) = \overline{d\mathring{H}^{k-1}(d)} \overset{\perp}{\oplus} \mathring{H}_0^k(d, \delta) \quad (2.3.3) \quad \{\text{decomposition\_c}$$

$$H_0^k(\delta) = \overline{\delta H^{k+1}(\delta)} \overset{\perp}{\oplus} \mathring{H}_0^k(d, \delta). \quad (2.3.4) \quad \{\text{decomposition\_c}$$

### 3 Simplicial topology

Before we can reformulate the boundary value problem in the language of differential forms we have to introduce some things from simplicial topology. This material is taken from [3] where a lot more details and results can be found.

#### 3.1 Simplicial complex

**Definition 3.1.1** (Affine simplex). Let  $x_0, x_1, \dots, x_k \in \mathbb{R}^n$  be affine independent. Then

$$[x_0, x_1, \dots, x_k] := \text{conv}\{x_0, \dots, x_k\}$$

is called an affine  $k$ -simplex. With  $\text{conv}$  we mean the convex combination.

We will assume all simplices to be affine.

**Definition 3.1.2** (Simplicial complex). A *simplicial complex*  $K$  is a collection of affine simplices s.t.

1.  $\sigma \in K \Rightarrow$  any face of  $\sigma$  is in  $K$ ,
2.  $\sigma, \tau \in K \Rightarrow \sigma \cap \tau$  is either empty or a face of both  $\sigma$  and  $\tau$ .

We call  $|K| := \bigcup\{\sigma \mid \sigma \in K\}$  the polyhedron of  $K$  and we denote the set of all  $k$ -simplices as  $K^{(k)}$ .

For any topological space  $X$  a homeomorphism  $\tau : |K| \rightarrow X$  is called *triangulation* of  $X$ . Let  $\{x_1, x_2, \dots\}$  be the vertices in the simplicial complex  $K$ . We fix an ordering of the vertices for every simplex. That means for any  $k$  every  $k$  simplex  $\sigma$  has a designated representation in the form of

$$\sigma = [x_{i_0}, x_{i_1}, \dots, x_{i_k}].$$

**Definition 3.1.3** (Star). The *star* of a vertex  $x_i$  is the collection of all simplices  $\sigma \in K$  s.t.  $x_i$  is contained in  $\sigma$ .

We call a simplicial complex *star-bounded* for some number  $N$  if the star of any vertex contains at most  $N$  simplices.

**Does this imply quasi-regularity?** Star-boundedness will be a crucial assumption later (see Assumption ??). Now we will introduce algebraic structures on the simplicial complex.



**Definition 3.1.4** (*k-chain*). Let  $K$  be a simplicial complex. By  $C_k(K)$  we will denote the free abelian group on the  $k$ -simplices i.e. the abelian group of all formal finite sums

$$\sum_{\sigma} n_{\sigma} \sigma$$

with  $\sigma$  being  $k$ -simplices. The elements of  $C_k(K)$  (i.e. sums of the above form) are called *k-chains*.

**Definition 3.1.5** (Boundary). We have the *boundary operator*  $\partial_k : C_k(K) \rightarrow C_{k-1}(K)$ . We first define it for any simplex  $[x_{i_0}, x_{i_1}, \dots, x_{i_k}]$

$$\partial[x_{i_0}, x_{i_1}, \dots, x_{i_k}] := \sum_{j=0}^k (-1)^j [x_{i_0}, x_{i_1}, \dots, \hat{x}_{i_j}, \dots, x_{i_k}]$$

where  $[x_{i_0}, x_{i_1}, \dots, \hat{x}_{i_j}, \dots, x_{i_k}]$  is the simplex without vertex  $x_{i_j}$ . We then extend the definition of the boundary operator linearly to  $k$ -chains  $c = \sum_{\sigma} c_{\sigma} \sigma$  by

$$\partial c := \sum_{\sigma} c_{\sigma} \partial \sigma.$$

By convention we define  $\partial_0 = 0$ . We will leave out the index  $k$  if it is clear from the context or irrelevant.

A crucial property of the chain operator is the following.

**Proposition 3.1.6.**  $\partial \circ \partial = 0$ .

*Proof.* This can be proven by direct computation, analogous to [3, Chap. 4, Lemma 1.6]  $\square$

We can now generalize the notions of the chain groups by using factor groups. Let  $L \subseteq K$  be a simplicial complex which we will call simplicial subcomplex. Then we define the factor group

$$C_k(K, L) := C_k(K) / C_k(L).$$

We denote the elements of  $C_k(K, L)$  i.e. the equivalence class by  $\underline{c}$  for some  $c \in C_k(K)$ . Because  $L$  is a simplicial complex we have  $\partial_k c \in C_{k-1}(L)$  for any  $c \in C_k(K)$ . Thus it induces a homomorphism on the factor groups denoted by

$$\underline{\partial}_k : C_k(K, L) \rightarrow C_{k-1}(K, L), \quad \underline{\partial}_k \underline{c} := \underline{\partial_k c}.$$

Note that  $C(K, L)$  generalizes the definition of  $C_k(K, L)$  because we can choose  $L = \emptyset$ . Then the abelian group on  $\emptyset$  is just  $\{0\}$  and thus  $C_k(K, L) = C_k(K)$ .

**Remark 3.1.7.** The last equality is technically not precise of course. However, for any group  $G$  with identity  $\iota$  the resulting factor group  $G/\{\iota\}$  every equivalence class  $\underline{g}$  would only include  $g$  itself so we can trivially identify  $G$  with  $G/\{\iota\}$  and we will do so from now on.

We want to investigate how we can understand  $\underline{c}$ .

**Proposition 3.1.8.** *Let  $c \in C_k(K)$  be arbitrary. Then*

$$\underline{c} = \underline{0} \leftrightarrow c = \sum_{\tau \in L} n_\tau \tau.$$

*As usual the right hand side is a finite sum. So for two  $k$ -chains  $c = \sum_\sigma n_\sigma \sigma \in C_k(K)$  and  $c' = \sum_\sigma n'_\sigma \sigma$  we have*

$$\underline{c} = \underline{c'} \leftrightarrow n_\sigma = n'_\sigma \quad \forall \sigma \in K \setminus L. \quad (3.1.1) \quad \{\text{eq:equivalence\_}\}$$

*Proof.*  $c \in \underline{0}$  is just equivalent to saying that  $c \in C_k(L)$  by definition of the factor group and thus we can write  $c = \sum_{\tau \in L} n_\tau \tau$ . (3.1.1) follows from that because  $\underline{c} = \underline{c'}$  is equivalent to  $\underline{c - c'} = \underline{0}$ .  $\square$

In this sense we can identify  $C_k(K, L)$  with formal sums of simplices in  $K^{(k)} \setminus L^{(k)}$ .

## 3.2 Simplicial (Co-)Homology

We call a  $k$ -chain  $\underline{c} \in C_k(K, L)$  a  $k$ -cycle if  $\partial \underline{c} = 0$  and we call  $\underline{c}$  a  $k$ -boundary if there exists  $\underline{d}$  s.t.  $\underline{c} = \partial \underline{d}$ . Let  $Z_k(K, L) = \ker \partial_k$  and  $B_k(K, L) = \text{im } \partial_{k-1}$ . We can now define the simplicial homology groups of our simplicial complex.

**Definition 3.2.1** (Simplicial homology). The relative homology groups  $H_k(K, L)$  are defined as

$$H_k(K) := Z_k(K, L) / B_k(K, L).$$

**Remark 3.2.2.** We call them relative homology group because define them on the for  $C_k(K, L)$ . The standard homology groups  $H_k(K)$  (i.e. taking  $L = \emptyset$ ) are independent of the chosen triangulation of  $|K|$  [3, p.248] because they are isomorphic to the singular homology groups which only depend on  $|K|$

Let  $G$  be any abelian group. Then we define the group of  $k$ -cochains  $C^k(K, L; G)$  by

$$C^k(K, L; G) := \text{Hom}(C_k(K, L), G)$$

i.e. the group of all homomorphisms from  $C_k(K, L)$  to  $G$ . We generally use the superindex  $^k$  if something is related to cochains and the subindex  $_k$  if it is related to chains. We now introduce an operator between the groups of cochains.

$C^k(K, L; G)$  can be identified with the cochains that vanish on  $L$ .

{prop:relative\_c

**Proposition 3.2.3.** *Define*

$$\tilde{C}^k(K, L; G) := \{F \in C^k(K; G) \mid F(c) = 0 \quad \forall c \in C_k(L)\}.$$

Then any  $F \in \tilde{C}^k(K, L; G)$  induces a homomorphism  $\underline{F} \in C^k(K, L; G)$  and  $j : \tilde{C}^k(K, L; G) \rightarrow C^k(K, L; G)$ ,  $F \mapsto \underline{F}$  is an isomorphism.

*Proof.* Because  $C_k(L) \subseteq \ker F$  is a subgroup we get the induced homomorphism

$$\underline{F} : C_k(K, L) = C_k(K) / C_k(L) \rightarrow G / 0 = G.$$

**$j$  is injective.** Let  $\underline{F}(\underline{c}) = 0$  for every  $c \in C_k(K)$ . Then  $F(c) = \underline{F}(\underline{c}) = 0$  so  $F = 0$ .  **$j$  is surjective.** Let  $\varphi \in C^k(K, L; G)$  be arbitrary. Then define  $F \in \tilde{C}^k(K, L; G)$ ,  $F(c) := \varphi(\underline{c})$ . We first have to show that  $F \in \tilde{C}^k(K, L; G)$ . For any  $d \in C_k(L)$  we get  $\underline{d} = 0 \in C_k(K, L)$  and  $F(d) = 0$ . Then we have for any  $\underline{c} \in C_k(K, L)$ ,  $\underline{F}(\underline{c}) = F(c) = \varphi(\underline{c})$  i.e.  $\underline{F} = \varphi$  which proves surjectivity.  $\square$

**Proposition 3.2.4.**  $j$  as defined in Prop. 3.2.3 is a chain map.

*Proof.* Let  $F \in \tilde{C}^k(K, L; G)$  be arbitrary. Then

$$\partial^k \underline{F}(\underline{c}) = \partial^k F(c) = F(\partial_k c) = \underline{F}(\partial_k \underline{c}) = \underline{\partial^k F}(\underline{c})$$

i.e.  $j \circ \partial^k = \underline{\partial^k} \circ j$  and  $j$  is a chain map.  $\square$

**Corollary 3.2.5.** The induced map  $[j] : H^k(K, L; G) \rightarrow \tilde{H}^k(K, L; G)$  is an isomorphism.

**Definition 3.2.6.** We define the operator  $\delta : C^k(K; G) \rightarrow C^{k+1}(K; G)$  via

$$(\delta f)(c) := f(\partial c).$$

for a  $(k+1)$ -chain  $c$ . We call a cochain  $f \in C^k(K; G)$  *closed* if  $\delta f = 0$  and we call  $f$  *exact* if there is a  $g \in C^{k+1}(K; G)$  s.t.  $f = \delta g$ .

We define the cohomology spaces analogous to homology spaces above.

**Definition 3.2.7** (Simplicial cohomology). Denote the closed  $k$ -cochains as  $Z^k(K; G)$  and the exact ones with  $B^k(K; G)$ . We then define the *simplicial cohomology groups*  $H^k(K)$  as

$$H^k(K; G) := Z^k(K; G) / B^k(K; G).$$

Note that in the case of  $G = \mathbb{R}$  this becomes a vector space. We will later show that if we consider certain subspaces of cochains so called *p*-summable cochains (see Def. ??) that the  $L_p$ -cohomology defined above and the cohomology spaces of these *p*-summable cochains are isomorphic.

Now of course there is the question how the homology and cohomology groups are related to each other. This question is answered by the *universal coefficient theorem*. But before we can formulate it we have to introduce exact sequences.

**Definition 3.2.8** (Exact sequence). Let  $(G_i)_{i \in \mathbb{Z}}$  be a sequence of groups and  $(f_i)_{i \in \mathbb{Z}}$  be a sequence of homomorphisms  $f_i : G_i \rightarrow G_{i+1}$ . Then this sequence of homomorphisms is called *exact* if  $\text{im } f_{i-1} = \ker f_i$ .

The universal coefficient theorem in the case of simplicial homology states that the sequence

$$0 \rightarrow \text{Ext}(H_{k-1}(K), G) \rightarrow H^k(K; G) \xrightarrow{\beta} \text{Hom}(H_k(K), G) \rightarrow 0 \quad (3.2.1) \quad \{\text{eq:universal\_coe}\}$$

is exact.  $\beta$  is defined via  $\beta([F])([c]) := F(c)$ . The definition of  $\text{Ext}$  can be found in [3], but it does not matter for our purpose because from now on we will assume  $G = \mathbb{R}$  and  $\text{Ext}(H_{k-1}(K), \mathbb{R}) = 0$ . This follows from the fact that  $\mathbb{R}$  is a divisible and hence injective abelian group. The definition these terms and the connections used can also be found in [3, Sec. V.6]. However, we will not dwelve into the algebraic background further. We can conclude from the exactness of the above short sequence that  $\ker \beta = 0$  and  $\text{im } \beta = \text{Hom}(H_k(K), \mathbb{R})$ . So  $\beta$  is a isomorphism.

### 3.3 De Rham's theorem

{sec:de\_rhams\_th

It turns out that the cochain cohomology is closely related to the cohomology of differential forms (??). Let us recall Stokes' theorem first which said that for a  $k$ -form  $\omega \in C_0^\infty \Lambda^k(M)$  for a smooth  $k$ -dimensional oriented manifold  $M$  we have

$$\int_M d\omega = \int_{\partial M} \omega.$$

The following details are taken from Section V.5 and V.9 from [3]. We will only focus on the main ideas and avoid dwelling into the technical details. The interested reader can find more arguments in the given reference.

Let now  $\sigma$  be a smooth  $k$ -simplex i.e.  $\sigma : \Delta_k \rightarrow M$  is smooth. We now define

$$\int_{\sigma} \omega = \int_{\Delta_k} \sigma^* \omega$$

and then we define the integral over a  $k$ -chain  $c = \sum_{\sigma} n_{\sigma} \sigma$

$$\int_c \omega = \sum_{\sigma} n_{\sigma} \int_{\sigma} \omega.$$

This motivates us to introduce the homomorphism  $I : C^{\infty} \Lambda^k(M) \rightarrow \text{Hom}(C_k; \mathbb{R})$  defined by

$$I(\omega)(c) = \int_c \omega.$$

**Remark 3.3.1.** There are some technical details that we will not go into details here, but that should be mentioned. First,  $\Delta_k$  is not a manifold. The  $(k-2)$  skeleton which are the corners for  $k=2$  and the edges for  $k=3$ . If we remove these points then  $\Delta_k$  is a manifold with boundary. But since this is a null-set w.r.t. the full simplex and the boundary as well, this does not matter. Second, Because we are integrating over the  $\Delta_k$  their orientation is important and has to be chosen consistently.

Using Stokes's theorem we observe

$$\begin{aligned} I(d\omega)(c) &= \sum_{\sigma} n_{\sigma} \int_{\sigma} d\omega = \sum_{\sigma} n_{\sigma} \int_{\Delta_k} \sigma^* d\omega = \sum_{\sigma} n_{\sigma} \int_{\Delta_k} d\sigma^* \omega = \sum_{\sigma} n_{\sigma} \int_{\partial \Delta_k} \sigma^* \omega \\ &= \int_{\sum_{\sigma} n_{\sigma} \partial \sigma} \omega = I(\omega)(\partial c) = \partial(I(\omega))(c) \end{aligned}$$

so we obtain

$$I(d\omega) = \partial(I(\omega)).$$

This implies that  $I$  induces a homomorphism on cohomology

$$[I] : H_{dR}^k(M) \rightarrow H^k(M; \mathbb{R}).$$

*De Rham's theorem* now states that this homomorphism is in fact an isomorphism.

### 3.4 Existence of uniqueness of cochain

As an application, we will show the following proposition which will be used later to show existence and uniqueness of a solution of the magnetostatic problem.

**Proposition 3.4.1.** *Assume that  $H_1(K, L) = \mathbb{Z}[\gamma]$  i.e. the homology class of the closed 1-chain  $\gamma$  is a generator of the first homology group. Then we have the following:*

- (i) *For any  $C_0 \in \mathbb{R}$  there exists a closed 1-chain  $F \in Z^1(K, L)$  with  $F(\gamma) = C_0$ ,*
- (ii) *any other  $G \in Z^1(K, L)$  with  $G(\gamma) = C_0$  is in the same cohomology class i.e.  $[F] = [G]$ .*

*Proof. Proof of (i)* Because  $[\gamma]$  is a generator of the homology group we obtain a homomorphism  $\hat{F} \in \text{Hom}(H_1(K, L), \mathbb{R})$  by fixing  $\hat{F}([\gamma]) = C_0$ . This determines the other values. Then we know from (3.2.1) that there exists a  $[F] \in H^1(K, L)$  with  $\beta([F]) = \hat{F}$  because  $\beta$  is an isomorphism. So we obtain

$$F(\gamma) = \beta([F])([\gamma]) = \hat{F}([\gamma]) = C_0.$$

**Proof of (ii)** Take  $[c] \in H_1(K, L)$  arbitrary. Then there exists  $n \in \mathbb{Z}$  s.t.  $[c] = n[\gamma]$ . Using  $\beta$  from (3.2.1) We have

$$\beta([F])([c]) = \beta([F])(n[\gamma]) = n\beta([F])([\gamma]) = nF(\gamma) = nG(\gamma) = \beta([G])([c])$$

and thus  $\beta([F]) = \beta([G])$ . Because  $\beta$  is an isomorphism we arrive at  $[F] = [G]$ .  $\square$

The following lemma will be needed later in Sec. ?? to prove existence and uniqueness of a solution of the magnetostatic problem. It is now useful to think of  $K$  as a triangulation of an exterior domain and  $L$  be the triangulation of the exterior of some ball  $\mathbb{R}^3 \setminus B_R$  with  $R > 0$  large enough. Then we assume for the simplicial subcomplex  $L$  that its geometric realization  $|L|$  is homeomorphic to  $\mathbb{R}^3 \setminus B_R$ .

First we need to understand how the zero-th homology group looks like. When we say path-connected we mean in the sense of simplicial topology i.e. we can connect all vertices with a 1-chain.

**Lemma 3.4.2.** *Let  $K$  be a path-connected simplicial complex. Then the homology class of every vertex  $[x_i] \in H_0(K)$  is a generator of the homology group.*

{lem:zeroth\_homo

*Proof.* The proof works exactly as the proof of Theorem IV.2.1 in [3] where we use the notion of path-connected on simplicial complexes.  $\square$

**Lemma 3.4.3.** *Let  $K, L$  be simplicial complexes with  $L \subseteq K$  and assume they are path-connected. Then the inclusion  $\iota : C_0(L) \hookrightarrow C_0(K)$  induces an isomorphism on homology.*

*Proof.* This follows immediately from Lemma 3.4.2.  $\square$

**Lemma 3.4.4.** *Let  $K$  and  $L$  be as in the previous lemma. Assume additionally that  $|L|$  is homeomorphic to  $\mathbb{R}^3 \setminus B_R$ . Then the natural surjection  $j : C_1(K) \rightarrow C_1(K, L)$  induces an isomorphism on homology.*

*Proof.* We have the exact sequence

$$\begin{array}{ccccc} H_1(L) & \xrightarrow{[\iota_1]} & H_1(K) & \xrightarrow{[j_1]} & H_1(K, L) \\ \xrightarrow{[\partial_1]} H_0(L) & \xrightarrow{[\iota_0]} & H_0(K) & \xrightarrow{[j_0]} & H_0(K, L). \end{array}$$

We know that  $H_1(L) \cong H_1(|L|) \cong H_1(\mathbb{S}^2) = 0$ . Because  $[\iota_0]$  is an isomorphism due to Lemma 3.4.3  $\text{im}[\partial_1] = 0$ . Thus, we get the exact sequence

$$0 \xrightarrow{[\iota_1]} H_1(K) \xrightarrow{[j_1]} H_1(K, L) \xrightarrow{[\partial_1]} 0$$

and so  $[j_1]$  is a isomorphism.  $\square$

Now using all these lemmas and results we can now prove the following important lemma that will be needed later in Sec. ??

**Lemma 3.4.5.** *Let  $K$  and  $L$  be as in the previous lemma and assume that  $H_1(K) = \mathbb{Z}[\gamma]$ . Then there exists a cochain  $F \in \tilde{C}^1(K, L)$  s.t.  $F(\gamma) = C_0$ .*

*Proof.* We know from Lemma 3.4.4 that  $[j] : H_1(K) \rightarrow H_1(K, L)$  is a isomorphism. Thus, we have  $[j]([\gamma]) = [\underline{\gamma}] \in H_1(K, L)$  is a generator. We can now apply Prop. 4.3.1 to get a  $\tilde{F} \in C^1(K, L)$  s.t.  $\tilde{F}(\underline{\gamma}) = C_0$ . Now we continue with Prop. 3.2.3 to get that there exists a unique  $F \in \tilde{C}^1(K, L)$  s.t.  $jF = \underline{F} = \tilde{F}$  and we arrive at

$$F(\gamma) = \underline{F}(\underline{\gamma}) = \tilde{F}(\underline{\gamma}) = C_0.$$

$\square$

## 4 Existence and uniqueness of solutions

In this section, we will apply the developed theory of the preceding chapters to prove the existence and uniqueness of the magnetostatic problem on exterior domains. With exterior domain we mean that our domain  $\Omega \subseteq \mathbb{R}^3$  is the complement of a compact set. The main motivation for this problem is the special case of  $\Omega$  being the complement of a torus. This is also the motivation behind the topological assumption that we will give. It might be useful to keep this example in mind.

Recall the magnetostatic problem we are studying.

{prob:magnetosta

**Problem 4.0.1.** Find  $B \in H_0(\text{div}; \Omega)$  s.t.

$$\text{curl } B = 0, \quad (4.0.1)$$

$$\text{div } B = 0 \text{ in } \Omega \text{ and} \quad (4.0.2)$$

$$\int_{\gamma} B \cdot dl = C_0. \quad (4.0.3)$$

Of course in order for the curve integral constraint to be well-defined we need to check the regularity of solutions. Then using the tools we developed in the previous sections we will proof existence and uniqueness.

### 4.1 Regularity of solutions

{sec:regularity\_

We will rely on standard regularity results about elliptic systems of the following form. Take  $A_{ij}^{\alpha\beta} \in \mathbb{R}$  for  $i, j, \alpha, \beta = 1, 2, 3$  and  $A_{ij}^{\alpha\beta} = A_{ji}^{\beta\alpha}$ . Then we have systems of the form

$$-\sum_{\alpha, \beta, j} \partial_{\alpha} (A_{ij}^{\alpha\beta} \partial_{\beta} B_j) = f_i - \sum_{\alpha} \partial_{\alpha} F_i^{\alpha} \quad (4.1.1) \quad \{\text{eq:elliptic_sys}$$

with data  $f_i, F_i^{\alpha} \in L^2(\Omega)$ . We call this system *elliptic* if  $A$  satisfies the Legendre condition i.e.

$$\sum_{\alpha, \beta, i, j} A_{ij}^{\alpha\beta} \xi_{\alpha}^i \xi_{\beta}^j \geq c |\xi|^2, \quad \forall \xi \in \mathbb{R}^{3 \times 3} \quad (4.1.2) \quad \{\text{eq:legendre_con}$$

with  $c > 0$ .  $|\xi|$  is here the Frobenius norm, but technically the chosen norm is irrelevant due to all norms on  $\mathbb{R}^{3 \times 3}$  being equivalent. We then call  $B$  a weak solution of the problem if

$$\int_{\Omega} \sum_{\alpha, \beta, i, j} A_{ij}^{\alpha\beta} \partial_{\beta} B_j \partial_{\alpha} \varphi_i dx = \int_{\Omega} \left\{ \sum_i f_i \varphi_i + \sum_{\alpha, i} F_i^{\alpha} \partial_{\alpha} \varphi_i \right\} dx \quad (4.1.3) \quad \{\text{eq:weak_ellipti}$$



for all  $\varphi \in C_0^1(\Omega; \mathbb{R}^3)$ . This formulation is taken from [1, Sec. 1.3]. At first we will slightly modify the notion of weak solution.

**Proposition 4.1.1.** *Assume that we have an elliptic system with constant coefficients i.e.  $A$  is constant. Then (4.1.3) is fulfilled for all  $\varphi \in C_0^1(\Omega; \mathbb{R}^3)$  if and only if it is fulfilled for  $\varphi \in C_0^\infty(\Omega; \mathbb{R}^3)$ .*

*Proof.* This follows by a simple density argument. Assume that (4.1.3) is fulfilled for all test functions in  $C_0^\infty(\Omega; \mathbb{R}^3)$ . Now take  $\varphi \in C_0^1(\Omega; \mathbb{R}^3)$  arbitrary. Because  $\varphi \in H_0^1(\Omega)^3$  and  $C_0^\infty(\Omega; \mathbb{R}^3)$  is dense in  $H_0^1(\Omega)^3$  we can find a sequence  $(\varphi^{(l)})_{l \in \mathbb{N}} \subseteq C_0^\infty(\Omega; \mathbb{R}^3)$  s.t.  $\varphi^{(l)} \rightarrow \varphi$  in  $H^1(\Omega)^3$ . Thus the partial derivatives converge in  $L^2(\Omega)$  and we get

$$\begin{aligned} \int_{\Omega} \sum_{i,j,\alpha,\beta} A_{ij}^{\alpha,\beta} \partial_{\beta} B_j \partial_{\alpha} \varphi_i dx &= \sum_{i,j,\alpha,\beta} A_{ij}^{\alpha,\beta} \int_{\Omega} \partial_{\beta} B_j \lim_{l \rightarrow \infty} \partial_{\alpha} \varphi_i^{(l)} dx \\ &\stackrel{L^2 \text{ limit}}{=} \lim_{l \rightarrow \infty} \int_{\Omega} \left\{ \sum_i f_i \varphi_i^{(l)} + \sum_{\alpha,i} F_i^{\alpha} \partial_{\alpha} \varphi_i^{(l)} \right\} dx = \int_{\Omega} \left\{ \sum_i f_i \varphi_i + \sum_{\alpha,i} F_i^{\alpha} \partial_{\alpha} \varphi_i \right\} dx. \end{aligned}$$

Since  $\varphi \in C_0^1(\Omega; \mathbb{R}^3)$  was arbitrary the first direction of the equivalence is proved. The other direction is trivial.  $\square$

So we see that in the case of constant coefficients we can consider just smooth compactly supported functions as test functions.

Next, we will state the crucial result about the regularity of elliptic systems which will give us the desired regularity. This is Theorem 2.13 and Remark 2.16 in [1] in slightly less generality.

**Theorem 4.1.2.** *Let  $\Omega$  be an open domain in  $\mathbb{R}^n$ . Let  $A$  be constant and satisfy the Legendre condition (4.1.2). Then for every  $B \in H_{loc}^1(\Omega)^3$  weak solution in the sense of (4.1.3) with  $f \in H_{loc}^k(\Omega)^3$  and  $F \in H_{loc}^{k+1}(\Omega; \mathbb{R}^{m \times n})$  we have  $B \in H_{loc}^{k+2}(\Omega)^3$ .*

**Corollary 4.1.3.** *If under the assumptions of the previous theorem we consider the homogeneous problem, i.e.*

$$\int_{\Omega} \sum_{\alpha,\beta,i,j} A_{ij}^{\alpha,\beta} \partial_{\beta} B_j \partial_{\alpha} \varphi_i dx = 0$$

for all  $\phi \in C_0^\infty(\Omega; \mathbb{R}^3)$ , then  $B$  is smooth.

It should be noted that this does not guarantee us any regularity on the boundary.

Before we can apply this result, we have to check whether a solution of our problem  $B$  is actually in  $H_{loc}^1(\Omega)^3$ .

{cor:smooth\_solu

**Theorem 4.1.4.** Assume  $B \in H(\operatorname{div}; \Omega) \cap H(\operatorname{curl}; \Omega)$ . Then  $B \in H_{loc}^1(\Omega)^3$ .

{thm:solution\_in

Note that we did not assume  $B$  to be a solution.

*Proof.* We know that for a function  $u \in H_0(\operatorname{curl}; U) \cap H(\operatorname{div}; U)$  for some smooth domain  $U$  we have  $u \in H^1(U)^3$  (cf. [7, Remark 3.48]). Our  $\Omega$  is just assumed to be open so we can not apply this result directly.

Take  $Q \subset\subset \Omega$  open and pre-compact. Then we can find an open cover of  $\overline{Q}$  with a finite set of open balls  $\{K_i\}_{i=1}^N$  s.t.  $K_i \subseteq \Omega$  and

$$\overline{Q} \subseteq \bigcup_{i=1}^N K_i.$$

As a open cover of a compact set we can find a smooth partition of unity  $\{\chi_i\}_{i=1}^N$  subordinate to  $\{K_i\}_{i=1}^N$ .  $(B\chi_i)|_{K_i} \in H_0(\operatorname{curl}; K_i) \cap H(\operatorname{div}; K_i)$  and thus  $(B\chi_i)|_{K_i} \in H^1(K_i)^3$  by the above mentioned result. Also because  $B\chi_i$  has compact support in  $K_i$  we can extend it by zero to obtain  $B\chi_i \in H^1(\mathbb{R}^3)^3$  where we abused the notation by denoting the extension the same. Whence,

$$B|_Q = \left( \sum_{i=1}^N \chi_i|_Q \right) B|_Q = \sum_{i=1}^N (\chi_i B)|_Q \in H^1(Q)$$

i.e.  $B \in H_{loc}^1(\Omega)^3$ . □

The following lemma is a reformulation of the differential operator  $\operatorname{grad} \operatorname{div} - \operatorname{curl} \operatorname{curl}$  which will be needed when we write our magnetostatic problem in the above standard elliptic form.

**Lemma 4.1.5.** Let  $F \in H_{loc}^2(\Omega)^3$ . Then

{lem:graddiv\_cur

$$\operatorname{grad} \operatorname{div} F - \operatorname{curl} \operatorname{curl} F = \begin{pmatrix} \Delta F_1 \\ \Delta F_2 \\ \Delta F_3 \end{pmatrix}.$$

*Proof.* By a simple calculation and changing the order of differentiation

$$\operatorname{grad} \operatorname{div} F = \begin{pmatrix} \partial_1^2 F_1 + \partial_1 \partial_2 F_2 + \partial_1 \partial_3 F_3 \\ \partial_1 \partial_2 F_2 + \partial_2^2 F_2 + \partial_2 \partial_3 F_3 \\ \partial_1 \partial_3 F_1 + \partial_2 \partial_3 F_2 + \partial_3^2 F_3 \end{pmatrix}$$

and

$$\begin{aligned} \operatorname{curl} \operatorname{curl} F &= \operatorname{curl} \begin{pmatrix} \partial_2 F_3 - \partial_3 F_2 \\ \partial_3 F_1 - \partial_1 F_3 \\ \partial_1 F_2 - \partial_2 F_1 \end{pmatrix} = \begin{pmatrix} \partial_2(\partial_1 F_2 - \partial_2 F_1) - \partial_3(\partial_3 F_1 - \partial_1 F_3) \\ \partial_3(\partial_2 F_3 - \partial_3 F_2) - \partial_1(\partial_1 F_2 - \partial_2 F_1) \\ \partial_1(\partial_3 F_1 - \partial_1 F_3) - \partial_2(\partial_2 F_3 - \partial_3 F_2) \end{pmatrix} \\ &= \begin{pmatrix} \partial_1 \partial_2 F_2 - \partial_2^2 F_1 - \partial_3^2 F_1 + \partial_1 \partial_3 F_3 \\ \partial_2 \partial_3 F_3 - \partial_3^2 F_2 - \partial_1^2 F_2 + \partial_1 \partial_2 F_3 \\ \partial_1 \partial_3 F_3 - \partial_3^2 F_2 - \partial_2^2 F_3 + \partial_2 \partial_3 F_2 \end{pmatrix} \end{aligned}$$

and so by subtracting the two expressions

$$\operatorname{grad} \operatorname{div} F - \operatorname{curl} \operatorname{curl} F = \begin{pmatrix} \partial_1^2 F_1 + \partial_2^2 F_1 + \partial_3^2 F_1 \\ \partial_1^2 F_2 + \partial_2^2 F_2 + \partial_3^2 F_3 \\ \partial_1^2 F_3 + \partial_2^2 F_3 + \partial_3^2 F_3 \end{pmatrix} = \begin{pmatrix} \Delta F_1 \\ \Delta F_2 \\ \Delta F_3 \end{pmatrix}.$$

□

We want to rewrite this system in the expression of the elliptic system (4.1.1). We can rewrite the Laplacian

$$-\Delta F_i = -\sum_{\alpha=1}^3 \partial_\alpha \partial_\alpha F_i = -\sum_{\alpha,\beta=1}^3 \partial_\alpha \delta_{\alpha,\beta} \partial_\beta F_i = -\sum_{\alpha,\beta,j=1}^3 \partial_\alpha \delta_{\alpha,\beta} \delta_{ij} \partial_\beta F_j$$

so we get  $A_{ij}^{\alpha\beta} = \delta_{ij} \delta_{\alpha\beta}$ . We have to check that the resulting differential operator is indeed elliptic, but this is trivial because for any  $(\xi_\alpha^i)_{1 \leq i, \alpha \leq 3}$  we get

$$\sum_{\alpha,\beta,i,j} A_{ij}^{\alpha\beta} \xi_\alpha^i \xi_\beta^j = \sum_{\alpha,\beta,i,j} \delta_{ij} \delta_{\alpha\beta} \xi_\alpha^i \xi_\beta^j = \sum_{\alpha,i} (\xi_\alpha^i)^2 = |\xi|^2$$

so the Legendre condition (4.1.2) is fulfilled and the resulting system is elliptic. The weak formulation is

$$\int_{\Omega} \sum_{\alpha,\beta,i,j} \delta_{ij} \delta_{\alpha\beta} \partial_\beta B_j \partial_\alpha \varphi_i dx = \sum_{i=1}^3 \int_{\Omega} \nabla B_i \cdot \nabla \varphi_i dx.$$

Here we can assume  $\varphi \in C_0^\infty(\Omega)^3$  because all coefficients are constant.

**Theorem 4.1.6** (Smoothness of solutions). *Let  $\Omega \subseteq \mathbb{R}^3$  open and  $B \in H(\operatorname{div}; \Omega) \cup H(\operatorname{curl}; \Omega)$  and*

$$\begin{aligned} \operatorname{curl} B &= 0, \\ \operatorname{div} B &= 0. \end{aligned}$$

*Then  $B$  is smooth.*

*Proof.* Take  $\varphi \in C_0^\infty(\Omega)^3$ . Then

$$0 = \int_{\Omega} \operatorname{div} B \operatorname{div} \varphi + \operatorname{curl} B \cdot \operatorname{curl} \varphi dx = - \int_{\Omega} B \cdot (\operatorname{grad} \operatorname{div} \varphi - \operatorname{curl} \operatorname{curl} \varphi) dx$$

$$\stackrel{\text{Lemma 4.1.5}}{=} - \int_{\Omega} B \cdot \begin{pmatrix} \Delta \varphi_1 \\ \Delta \varphi_2 \\ \Delta \varphi_3 \end{pmatrix} = \sum_{i=1}^3 \int_{\Omega} \nabla B_i \cdot \nabla \varphi_i dx.$$

Note that the last integration by parts is well defined because  $B \in H_{loc}^1(\Omega)$  according to Thm. 4.1.4. So  $B$  is a weak solution of the elliptic system given by  $A_{ij}^{\alpha\beta} = \delta_{ij} \delta_{\alpha\beta}$ . Because we look at the homogenous problem our right hand side is obviously smooth and thus  $B$  is smooth as well due to Cor. 4.1.3.  $\square$

**Remark 4.1.7.** Obviously, the above arguments can be generalized by using a non-zero right hand side of our problem. Then we will in general not obtain a smooth solution, but for a sufficiently regular right hand side the curve integral would still be well-defined. [How much regularity? Source?](#)

## 4.2 Reformulation of the problem

We will return now to the magnetostatic problem. In order to use the results above we will reformulate the problem in the notation of differential forms. From now on we assume  $n = 3$  i.e. we are in three dimensional space. There are two ways to identify a vector field with a differential form (cf. [2, Table 6.1 and p.70]) either as a 1-form or a 2-form. For a vector field  $B$  we define

$$F^1 B := B_1 dx_1 + B_2 dx_2 + B_3 dx_3 \text{ and}$$

$$F^2 B := B_2 dx_2 \wedge dx_3 - B_1 dx_1 \wedge dx_3 + B_3 dx_1 \wedge dx_2$$

as the corresponding 1-form and 2-form. Then the exterior derivative is  $dF^2 \omega$  corresponds to the divergence, the codifferential  $\delta F^2 \omega$  corresponds to the curl and the normal component being zero on the boundary corresponds to  $\omega \in \mathring{H}^2(d)$ . [\[empty citation\]](#).

If we then use the association of 3-forms with scalars we have the corresponding boundary value problem without the integral condition for 2-forms: Find  $\omega \in \mathring{H}^2(d)$  s.t.

$$\delta \omega = 0, \tag{4.2.1}$$

$$d\omega = 0 \text{ in } \Omega. \tag{4.2.2}$$

Next, we have to add the integral condition. We remind the reader that we are in three dimensions so  $** = \operatorname{Id}$  and observe

$$\begin{aligned} *F^2 B &= B_1 **dx_1 + B_2 **dx_2 + B_3 **dx_3 = B_1 dx_1 + B_2 dx_2 + B_3 dx_3 \\ &= F^1 B. \end{aligned}$$

: Actually, we already use the Hodge star to define the vector proxies. So of course the vector proxy of the Hodge star will be the same. Then we have

$$\int_{\gamma} *F^2 B = \int_{\gamma} F^1 B = \int_{\gamma} B \cdot dl.$$

In the last step we used the fact that the integration of a 1-form over a curve is equivalent to the curve integral of the associated vector field (cf. [2, Sec. 6.2.3]). Hence, we can add the integral condition

$$\int_{\gamma} *\omega = C_0. \quad (4.2.3) \quad \{\text{integral\_condit}$$

However, we have only  $\omega \in \mathring{H}_0^2(d, \delta)$  so  $*\omega \in H^1(d)$  so this integral might not be well defined. In order to deal with this, we will again use the operator  $\mathcal{R}$  from Sec. ??.

We know from Thm. ?? that  $\mathcal{R}*\omega \in S_2^1(\bar{\Omega})$ . Using the operator  $\varphi$  from ?? we obtain  $\varphi\mathcal{R}*\omega \in S_2^1(K)$ . Now we know from Sec. ?? that the integration mapping  $I : S_2^1(K) \rightarrow C_2^1(K)$  is well-defined. Denote  $\bar{I} := I \circ \varphi \circ \mathcal{R}$  and let us replace the integral condition (??) with

$$\bar{I}(*\omega)(\gamma) = C_0.$$

Of course, we have to justify why this is reasonable. So let us take  $\eta \in S_2^1(\bar{\Omega})$ . That means we can integrate it directly using the definition from ??. Let us also assume that  $\eta$  is closed and  $\int_{\gamma} \eta = C_0$ . Then we know from Thm. ??

$$\mathcal{R}\eta = \eta + d\mathcal{A}\eta + \mathcal{A}d\eta \stackrel{\eta \text{ closed}}{=} \eta + d\mathcal{A}\eta.$$

We know further that  $\mathcal{A}\eta \in S_2^0(\bar{\Omega})$ . Apply  $\varphi$  on both sides and use that fact that it commutes ?? with the exterior derivative to get

$$\varphi\mathcal{R}\eta = \varphi\eta + d\varphi\mathcal{A}\eta.$$

$[I]$  is an isomorphism of cohomology and thus sends exact S-forms to exact cochains.  $\gamma$  is closed so  $I(d\varphi\mathcal{A}\eta)(\gamma) = 0$  and we conclude

$$\bar{I}(\eta)(\gamma) = I(\varphi\mathcal{R}\eta)(\gamma) = I(\varphi\eta) \stackrel{\text{by def.}}{=} I(\eta),$$

i.e. the integral remains unchanged if we integrate closed forms over closed chains. Because  $*\omega$  is closed we thus do not change the integral if the curve integral  $*\omega$  would already have been well defined before.

To summarize we obtain the following problem.

**Problem 4.2.1.** Find  $\omega \in \mathring{H}^2(d; \Omega)$  s.t.

$$\begin{aligned} d\omega &= 0, \\ \delta\omega &= 0 \text{ in } \Omega, \\ \bar{I}(*\omega)(\gamma) &= C_0. \end{aligned}$$

We will examine existence and uniqueness of this problem in the next section.

### 4.3 Existence and uniqueness

The curve integral condition is closely linked to the topology of our domain which we will have to use in our proof. This will rely on the tools of homology from Sec. ?? . Because of this connection if we want the curve integral to give us uniqueness of the solution we need to assume certain topological properties. In our case, this will be the condition that our first homology group is generated by the curve that we are integrating over i.e.

$$H_1(\Omega) = \mathbb{Z}[\gamma].$$

Then we get the following existence and uniqueness result on the level of homology.

**Proposition 4.3.1.** *Assume that  $H_1(\Omega) = \mathbb{Z}[\gamma]$  i.e. the homology class of the closed 1-chain  $\gamma$  is a generator of the first homology group. Then we have the following:*

- (i) *For any  $C_0 \in \mathbb{R}$  there exists a closed 1-cochain  $F \in Z^1(\Omega)$  with  $F(\gamma) = C_0$ ,*
- (ii) *any other  $G \in Z^1(\Omega)$  with  $G(\gamma) = C_0$  is in the same cohomology class i.e.  $[F] = [G]$*

*i.e. the cochain is unique up to cohomology.*

*Proof. Proof of (i)* Because  $[\gamma]$  is a generator of the homology group we obtain a homomorphism  $\hat{F} \in \text{Hom}(H_1(\Omega), \mathbb{R})$  by fixing  $\hat{F}([\gamma]) = C_0$ . This determines the other values. Then we know from (3.2.1) that there exists a  $[F] \in H^1(\Omega)$  with  $\beta([F]) = \hat{F}$  because  $\beta$  is a isomorphism. So we obtain

$$F(\gamma) = \beta([F])([\gamma]) = \hat{F}([\gamma]) = C_0.$$

**Proof of (ii)** Take  $[c] \in H_1(\Omega)$  arbitrary. Then there exists  $n \in \mathbb{Z}$  s.t.  $[c] = n[\gamma]$ . Using  $\beta$  from (3.2.1) We have

$$\beta([F])([c]) = \beta([F])(n[\gamma]) = n\beta([F])([\gamma]) = nF(\gamma) = nG(\gamma) = \beta([G])([c])$$

and thus  $\beta([F]) = \beta([G])$ . Because  $\beta$  is an isomorphism we arrive at  $[F] = [G]$ .  $\square$

This abstract topological result can now be linked to the differential forms via the de Rham isomorphism from Sec.3.3. We will formulate it in a way that demonstrates the connection of differential forms and cochains.

{cor:existence\_u

**Corollary 4.3.2.** *Assume  $H_1(\Omega) = \mathbb{Z}[\gamma]$  as above. Then*

(i) *For any  $C_0 \in \mathbb{R}$  there exists a closed smooth 1-form  $\theta \in \mathfrak{Z}^1(\Omega)$  with*

$$I(\theta)(\gamma) = \int_{\gamma} \theta = C_0$$

(ii) *any other  $\eta \in \mathfrak{Z}^1(\Omega)$  with*

$$I(\eta)(\gamma) = \int_{\gamma} \eta = C_0$$

*is in the same cohomology class of  $H_{dR}^1(\Omega)$  i.e.  $[\eta] = [\theta]$ .*

*Proof. Proof of (i)* Recall from Sec.3.3 that the integration of differential forms over chains induces an isomorphism on cohomology  $[I] : H_{dR}^1(\Omega) \rightarrow H^1(\Omega)$  which we call de Rham isomorphism. We know from Prop.4.3.1 that there exists  $F \in H^1(\Omega)$  s.t.  $F(\gamma) = C_0$ . The surjectivity of the de Rham isomorphism now gives us  $[\theta] \in H^1(\Omega)$  s.t.

$$[I(\theta)] = [I](\theta) = [F]$$

i.e.

$$I(\theta) = F + \partial^0 J$$

with  $J \in C^0$ . Then,

$$I(\theta)(\gamma) = F(\gamma) + \partial^0 J(\gamma) = C_0 + J(\partial_1 \gamma) \stackrel{\gamma \text{ closed}}{=} C_0.$$

**Proof of (ii)** We have  $I(\eta)$  is a 1-cochain with  $I(\eta)(\gamma) = C_0$ . Thus, we can apply Prop.4.3.1 to get

$$[I](\eta) = [I(\eta)] = [I(\theta)] = [I](\theta).$$

Because  $[I]$  is an isomorphism we can conclude  $[\eta] = [\theta]$ .  $\square$

**Theorem 4.3.3** (Existence of solution). *Let  $\Omega \subseteq \mathbb{R}^3$  be such that  $\mathbb{R}^3 \setminus \Omega$  is compact. For the topology, we require that  $H_1(\Omega) = \mathbb{Z}[\gamma]$  for a 1-chain  $\gamma$ . Assume further that there exists an  $\epsilon$ -neighborhood*

{thm:existence}

$$\Omega_\epsilon := \{x \in \mathbb{R}^3 \mid d(x, \Omega) < \epsilon\}$$

s.t.  $H_1(\Omega_\epsilon) = \mathbb{Z}[\gamma]$  as well. Then there exists a solution to Problem 4.2.1.

Let us say a view words about the topological assumption regarding  $\Omega_\epsilon$ . This just means that we can slightly increase the domain without changing the first homology group. As an example, think again of a torus in  $\mathbb{R}^3$ . Assuming the torus has non-empty interior we can slightly reduce the poloidal radius without changing the topology of its the exterior domain.

*Proof.* At first we want to find a smooth differential 1-form  $\theta \in \Lambda^1(\Omega)$  with the desired curve integral. In order to do that we will increase the domain slightly. We start by referring to Cor. 4.3.2 to get a smooth differential form  $\tilde{\theta} \in \Lambda^1(\Omega_\epsilon)$  with

$$\int_\gamma \tilde{\theta} = C_0. \quad (4.3.1) \quad \{\text{eq:integral\_the}\}$$

We now refer back to ?? to change back to vector proxies. Let  $\tilde{\phi}$  be the vector proxy of  $\tilde{\theta}$  i.e.  $\tilde{\phi} \in C^\infty(\tilde{\Omega})^3$ . Because  $\tilde{\theta}$  is closed and (4.3.1) holds we obtain the corresponding properties of  $\tilde{\phi}$  which are

$$\begin{aligned} \int_\gamma \tilde{\phi} \cdot dl &= C_0 \\ \text{curl } \tilde{\phi} &= 0. \end{aligned}$$

We define  $\phi$  by restricting  $\tilde{\phi}$  to  $\Omega$ . Let now  $K_R$  be the open ball around the origin with radius  $R > 0$  large enough s.t.  $\Omega^c \subseteq K_R$  and  $\gamma \subseteq K_R$ . We now restrict  $\theta$  further to  $\Omega_R := \Omega \cap K_R$ . We denote the restriction with  $\phi_R := \phi|_{\Omega_R}$ .

We now need to construct a harmonic vector field with zero tangential trace s.t. we can extend it by zero. We do this by using the Hodge decomposition for 1-forms on  $\Omega_R$  in the 3D case ?. We project  $\phi_R$  onto the harmonic fields to obtain  $B_R$  which has zero tangential trace. So there exists a sequence  $(\psi_i)_{i \in \mathbb{N}} \in H^1(\Omega_R)$  s.t.

$$B_R = \phi_R - \lim_{i \rightarrow \infty} \nabla \psi_i$$



We also know that  $B_R$  is smooth because it is curl and divergence free from the section about the smoothness of solutions (Sec. 4.1). We want to check that the curve integral did not change. We know from ?? that the image of the exterior derivative is closed on bounded domains. Formulated in vector proxies, this means that  $\nabla H^1(U)$  is closed in  $L^2$  if  $U$  is a bounded domain. So we get that

$$\lim_{i \rightarrow \infty} \nabla \psi_i = \nabla \psi_R$$

with  $\psi_R \in H^1(\Omega_R)$ . Because  $B_R$  and  $\phi_R$  are smooth  $\psi_R$  must be smooth as well and so we have

$$\int_{\gamma} B_R \cdot dl = \int_{\gamma} \phi_R \cdot dl.$$

Now extend  $B_R$  by zero onto  $\mathbb{R}^3 \setminus K_R$ . Denote this extension as  $\overline{B}_R$ . Because  $B_R$  has tangential trace zero and is curl-free its extension  $\overline{B}_R \in H(\text{curl}; \Omega)$  and is also curl-free. Here it is important to remember that  $\mathbb{R}^3 \setminus K_R \subseteq \Omega$ . That means of course that  $\overline{B}_R$  might not be smooth on  $\partial K_R$  as it might have a jump. Now we can once again use the Hodge decomposition of two forms. This time on the whole domain  $\Omega$  to find a harmonic field  $B$  and a sequence  $(\rho_i)_{i \in \mathbb{N}}$  s.t.

$$\overline{B}_R = B + \lim_{i \rightarrow \infty} \nabla \rho_i.$$

Notice that because  $B$  is a harmonic vector field and because it is the vector proxy of a harmonic 2-form it already satisfies the Neumann boundary condition and it is divergence as well as curl free. That means  $B$  is a solution if the curve integral condition is satisfied. In order to see this, note that we have on  $K_R$

$$B_R = B|_{K_R} + \lim_{i \rightarrow \infty} \nabla \rho_i|_{K_R}.$$

Because the image of the gradient is closed on bounded domains we have  $\rho_R \in H^1(K_R)$  s.t.

$$B_R = B|_{K_R} + \nabla \rho_R.$$

With the same argument as above,  $\rho_R$  must be smooth and so

$$\int_{\gamma} B \cdot dl = \int_{\gamma} B|_{K_R} \cdot dl = \int_{\gamma} B_R \cdot dl = C_0$$

and thus  $B$  is indeed a solution. □

In the proof of uniqueness we will use the following lemma.

{lem:gradient\_se

**Lemma 4.3.4.** *Let  $\phi \in L^2_{loc}(\Omega_\epsilon)$  with  $\nabla\phi \in L^2(\Omega)^3$ . Then there exists a sequence  $(\phi_i)_{i \in \mathbb{N}} \subseteq H^1(\Omega)$  s.t.  $\nabla\phi_i \rightarrow \nabla\phi$  in  $L^2(\Omega)^3$ .*

*Proof.* Take  $K_R$  the open ball around the origin with  $R$  large enough s.t.  $(K_R)^c \subseteq \Omega$ . Define  $\Omega_R := K_R \cap \Omega$ . Then  $\bar{\Omega}_R \subseteq K_{R+1}$ , where  $K_{R+1}$  is the open ball around the origin with radius  $R+1$ ,  $\Omega_R$  is a Lipschitz domain and  $K_{R+1}$  is pre-compact and  $\phi|_{\Omega_R} \in W^{1,2}(\Omega_R)$ . Note that here we need the fact that  $\phi \in L^2_{loc}(\Omega_\epsilon)$  because then  $\Omega_R$  is pre-compact in  $\Omega_\epsilon$ . Therefore we can find an extension  $E\phi \in W^{1,2}_0(\Omega_{R+1}) \hookrightarrow W^{1,2}(\mathbb{R}^3)$  (cf. [6, Sec.1.5.1]). So we can now define

$$\bar{\phi} := \begin{cases} \phi & \text{in } \Omega \\ E\phi & \text{in } \Omega^c. \end{cases}$$

Then  $\bar{\phi} \in L^2_{loc}(\mathbb{R}^3)$  and  $\nabla\bar{\phi} \in L^2(\mathbb{R}^3)^3$ . Then there exists a sequence  $(\phi_l)_{l \in \mathbb{N}} \subseteq C^\infty_0(\mathbb{R}^3)$  s.t.  $\nabla\phi_l \rightarrow \nabla\bar{\phi}$  in  $L^2(\mathbb{R}^3)^3$  (cf. [8, Lemma 1.1]). By restricting  $\phi_l$  to  $\Omega$  we obtain the result.  $\square$

**Theorem 4.3.5.** *Let the same assumptions hold as in Thm. 4.3.3. Then the solution of the problem is unique.*

*Proof.* Let  $B$  and  $\tilde{B}$  both be solutions and denote with  $\omega$  and  $\tilde{\omega}$  the corresponding 1-forms. So we have  $I(\omega)(\gamma) = I(\tilde{\omega})(\gamma) = C_0$ . Then we know from Cor. 4.3.2 that  $\omega$  and  $\tilde{\omega}$  are in the same cohomology in  $\mathcal{H}^1$ . This is equivalent to saying that there exists a smooth  $\mu$  s.t.

$$B - \tilde{B} = \text{grad } \mu.$$

However,  $\mu$  need not be in  $L^2$  since  $\Omega$  is unbounded. But we know that  $\text{grad } \mu \in L^2(\Omega)^3$  and  $\mu \in L^2_{loc}(\Omega)$ . Here we can now apply Lemma 4.3.4 and conclude

$$B - \tilde{B} \in \overline{\text{grad } H^1(\Omega)}.$$

Now remembering the Hodge decomposition in the 3D case we know

$$B - \tilde{B} \in \overline{\text{grad } H^1(\Omega)}^\perp$$

as well and thus  $B = \tilde{B}$  which concludes the proof of uniqueness.  $\square$

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