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# Sobolev Spaces

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# Chapter 1

## Introduction

In order to have classical solutions to partial differential equations (PDEs), it is often necessary that parameter functions in the PDE are regular enough or the domain where the PDE is considered has a regular boundary (e.g. no edge). However, in applications or in nature, these regularity assumptions are often not satisfied. Hence, a fundamental concept in the theory of PDEs is the concept of weak solutions which is also the basis for important numerical methods (e.g. the finite element method). The definition of these weak solutions is based on a concept of generalized derivatives of functions, the so called *weak derivatives*. *Sobolev spaces* are Banach spaces consisting of functions with weak derivatives. Important properties of these spaces will be studied in this lecture and will be a basis to study weak solutions of PDEs afterwards. Let us start by illustrating the idea behind weak solutions with an example.

**Example 1.1.** Let  $\Omega = (0, 1) \subseteq \mathbb{R}$  and  $f \in C^0(\overline{\Omega})$  be given. We look for a solution  $u \in C^2(\overline{\Omega})$  to the Poisson equation in one dimension,

$$(1.1) \quad \begin{aligned} -u'' &= f(x), & x \in \Omega, \\ u(x) &= 0, & x \in \{0, 1\} = \partial\Omega. \end{aligned}$$

$u$  e.g. describes the displacement of a rod which is fixed at  $x = 0$  and  $x = 1$ , where  $f$  is a force acting on the string. Of course the force  $f$  is not necessarily continuous in  $\overline{\Omega}$  and could have jumps.

In order to get a weaker solution concept, let  $\varphi \in C_0^\infty(\Omega)$  (infinitely often differentiable with compact support in  $\Omega$ ). Then integration by parts shows

$$\int_0^1 -u''(x)\varphi(x) \, dx = -u'(1)\varphi(1) + u'(0)\varphi(0) + \int_0^1 u'(x)\varphi'(x) \, dx.$$

Hence, in view of (1.1)

$$(1.2) \quad \int_\Omega u'(x)\varphi'(x) \, dx = \int_\Omega f(x)\varphi(x) \, dx \quad \text{for all } \varphi \in C_0^\infty(\Omega).$$

For (1.2) to be meaningful we do not need a second derivative of  $u$ . Moreover,  $f$  only has to be integrable instead of continuous. (1.2) will even make sense if  $u'$  is only a weak derivative of  $u$  as we will see soon.  $\square$

In order to motivate the definition of weak derivatives, we note the following identity.

**Lemma 1.2.** *Let  $\Omega \subseteq \mathbb{R}^n$  be open and  $u \in C^1(\Omega)$ . Then for  $i \in \{1, \dots, n\}$  we have*

$$(1.3) \quad \int_{\Omega} \frac{\partial u}{\partial x_i} \varphi \, dx = - \int_{\Omega} u \frac{\partial \varphi}{\partial x_i} \, dx \quad \text{for all } \varphi \in C_0^\infty(\Omega).$$

*Proof.* As in general neither  $\partial\Omega$  nor the boundary of the support of  $\varphi$  need to be regular, the proof is not immediate. Define

$$w(x) := \begin{cases} u(x)\varphi(x), & x \in \Omega, \\ 0, & x \in \mathbb{R}^n \setminus \Omega. \end{cases}$$

As  $w \in C^1(\Omega)$  and  $w = 0$  in a neighborhood of  $\partial\Omega$ , we conclude that  $w \in C^1(\mathbb{R}^n)$ . Take an open ball  $B$  large enough such that it contains the support of  $\varphi$ . Then by Gauß' (or Green's formula) we have

$$\int_{\Omega} w_{x_i} \, dx = \int_{\partial B} w_{x_i} \cdot \nu_i \, d\sigma = 0,$$

where  $\nu$  is the outward unit normal on  $\partial B$ . Hence, the product rule implies (1.3).  $\square$

(1.3) makes sense even if  $u, \frac{\partial u}{\partial x_i} \in L^1_{\text{loc}}(\Omega)$  (integrable on any bounded set  $V$  with  $\overline{V} \subset \Omega$ ).

Hence, we define weak derivatives by:

**Definition 1.3.** Let  $\Omega \subseteq \mathbb{R}^n$  be open,  $u \in L^1_{\text{loc}}(\Omega)$  and  $i \in \{1, \dots, n\}$ .  $u$  has the *weak partial derivative*  $\frac{\partial u}{\partial x_i}$  if there is  $v \in L^1_{\text{loc}}(\Omega)$  such that

$$(1.4) \quad \int_{\Omega} u(x) \frac{\partial \varphi}{\partial x_i}(x) \, dx = - \int_{\Omega} v(x) \varphi(x) \, dx \quad \text{for all } \varphi \in C_0^\infty(\Omega).$$

Then  $\frac{\partial u}{\partial x_i} := v$ .

Let us see in an example which functions have weak derivatives and how to calculate them.

**Example 1.4.** a) If  $u \in C^1(\Omega)$ , then by Lemma 1.2 (1.4) is satisfied with  $v := \frac{\partial u}{\partial x_i}$ . Hence,  $u$  is weakly differentiable and the weak derivative  $\frac{\partial u}{\partial x_i}$  coincides with the classical derivative.

b) Let  $\Omega = (-1, 1) \subset \mathbb{R}$ ,  $u(x) := |x|$  for  $x \in \Omega$ . Then as  $u \in C^1(\overline{\Omega} \setminus \{0\}) \cap C^0(\overline{\Omega})$ , we may use the fundamental theorem of calculus to obtain for  $\varphi \in C_0^\infty(\Omega)$ :

$$\begin{aligned} \int_{\Omega} u(x) \varphi'(x) \, dx &= \int_{-1}^0 -x \varphi'(x) \, dx + \int_0^1 x \varphi'(x) \, dx \\ &= \int_{-1}^0 \varphi(x) \, dx + (-x \varphi(x)) \Big|_{-1}^0 - \int_0^1 \varphi(x) \, dx + (x \varphi(x)) \Big|_0^1 \\ &= - \int_{-1}^0 1 \varphi(x) \, dx - \int_0^1 1 \varphi(x) \, dx = - \int_{-1}^1 v(x) \varphi(x) \, dx \end{aligned}$$

$$\text{if we define } v(x) = \begin{cases} 1, & x \in (0, 1), \\ -1, & x \in (-1, 0). \end{cases}$$

Then  $v \in L^1(\Omega)$  and since  $\{0\}$  is a set of measure zero in  $\mathbb{R}$ , we could define  $v(0)$  arbitrarily. Hence,  $u$  is weakly differentiable with derivative  $u' = v$ .  $u'$  coincides with the classical derivative in all  $x \in \Omega$  where the latter exists.

c) Defining again  $\Omega = (-1, 1)$  and  $v$  as in b), we have  $v \in L^1_{\text{loc}}(\Omega)$  and for all  $\varphi \in C_0^\infty(\Omega)$  we have

$$\int_{\Omega} v(x) \varphi'(x) dx = \int_{-1}^0 -\varphi'(x) dx + \int_0^1 \varphi'(x) dx = -\varphi(0) + \varphi(-1) + \varphi(1) - \varphi(0) = -2\varphi(0).$$

Now if  $v$  would be weakly differentiable, there would be  $w \in L^1_{\text{loc}}(\Omega)$  with

$$(1.5) \quad -2\varphi(0) = - \int_{\Omega} w(x) \varphi(x) dx \quad \text{for all } \varphi \in C_0^\infty(\Omega).$$

Fix some  $f \in C_0^\infty((-1, 1))$  with  $f(0) = 1$  and define  $\varphi_n(x) = f(nx)$  for  $x \in (-1, 1)$ ,  $n \in \mathbb{N}$  (where  $f = 0$  on  $\mathbb{R} \setminus (-1, 1)$ ). Then  $\varphi_n \in C_0^\infty((-1, 1))$  with  $\varphi_n(x) = 0$  for all  $x \in \mathbb{R} \setminus (-\frac{1}{n}, \frac{1}{n})$  with  $\varphi_n(0) = 1$  and  $\lim_{n \rightarrow \infty} \varphi_n(x) = 0$  for all  $x \in \Omega \setminus \{0\}$ . As  $\|\varphi_n\|_{L^\infty(\Omega)} \leq \|f\|_{L^\infty(\Omega)} < \infty$ , we conclude from the dominated convergence theorem that

$$0 = \lim_{n \rightarrow \infty} \left( - \int_{\Omega} w(x) \varphi_n(x) dx \right) \neq -2 = \lim_{n \rightarrow \infty} -2\varphi_n(0)$$

which contradicts (1.5). Hence,  $v$  is not weakly differentiable in  $\Omega$ .  $\square$

Hence, there are functions which are not classically differentiable everywhere and have weak derivatives, but there are also functions being not weakly differentiable (although  $v \in C^1(\Omega \setminus \{0\})$  in Example 1.4).

If we define the *Sobolev space*

$$W^{1,p}(\Omega) := \left\{ u \in L^p(\Omega) : \frac{\partial u}{\partial x_i} \text{ exists in the weak sense, } \frac{\partial u}{\partial x_i} \in L^p(\Omega) \text{ for all } i \in \{1, \dots, n\} \right\}$$

for  $p \in [1, \infty]$ , this is a Banach space which will turn out to be particularly useful in the context of weak solutions of PDEs. So we will study important properties of these spaces (and its generalisations to higher order derivatives) and finally will show how to use them for obtaining weak solutions of PDEs. We shortly illustrate the latter in an example.

**Example 1.5.** We continue Example 1.1 with  $\Omega = (0, 1) \subset \mathbb{R}$  and assume that  $f \in L^2(\Omega)$ . Then in view of (1.2) we say that  $u$  is a *weak solution* to (1.1) if  $u \in W^{1,2}(\Omega)$ ,

$$\int_{\Omega} u'(x) \varphi'(x) dx = \int_{\Omega} f(x) \varphi(x) dx \quad \text{for all } \varphi \in C_0^\infty(\Omega),$$

where  $u'$  is the weak derivative of  $u$ , and if  $u$  satisfies  $u = 0$  on  $\partial\Omega$  in a certain weak sense. The latter will be specified in a detailed way in Chapter 7 as  $u \in W^{1,2}(\Omega)$  is not necessarily continuous. In Chapter 7, we will study the generalisation of (1.1) for  $\Omega \subset \mathbb{R}^n$  being a bounded domain namely the Poisson equation

$$-\Delta u = f \text{ in } \Omega, \quad u = 0 \text{ on } \partial\Omega.$$

## Chapter 2

# Some Facts about Lebesgue Spaces

## $L^p(\Omega)$

Here, we recall some facts about Lebesgue spaces which should be known from previous lectures. Throughout this lecture, a set  $\Omega \subset \mathbb{R}^n$  is called *measurable* if it is measurable w.r.t. the Lebesgue measure on  $\mathbb{R}^n$ . Unless otherwise stated, we always assume in this chapter that  $\Omega \subset \mathbb{R}^n$  is measurable.

Then  $u: \Omega \rightarrow [-\infty, \infty]$  is measurable *on*  $\Omega$  if  $\{x \in \Omega: u(x) > \alpha\}$  is measurable for any  $\alpha \in \mathbb{R}$ .

### 2.1 $L^p(\Omega)$ : Definition and Basic Properties

- i) If  $u, v: \Omega \rightarrow [-\infty, \infty]$  are measurable on  $\Omega$ , they are equivalent if  $u = v$  a.e. in  $\Omega$ .  $[u]$  is the equivalence class of  $u$ . We always identify a function  $u$  with its equivalence class.
- ii) For  $p \in [1, \infty]$ , we define the Lebesgue space

$$L^p(\Omega) := \{u: \Omega \rightarrow [-\infty, \infty]: u \text{ measurable}, \|u\|_{L^p(\Omega)} < \infty\},$$

where

$$\begin{aligned} \|u\|_{L^p(\Omega)} &= \left( \int_{\Omega} |u(x)|^p dx \right)^{\frac{1}{p}} \text{ if } p \in [1, \infty), \\ \|u\|_{L^\infty(\Omega)} &= \operatorname{ess\,sup}_{x \in \Omega} |u(x)|. \end{aligned}$$

With the convention from i),  $u = 0$  in  $L^p(\Omega)$  if  $u = 0$  a.e. in  $\Omega$ . If  $[u]$  contains a continuous function, we assume that  $u$  is chosen to be continuous.

- iii)  $L^p(\Omega)$  is a Banach space for  $p \in [1, \infty]$ , i.e. a complete and normed vector space.
- iv)  $L^p$  convergence and a.e. convergence: Let  $p \in [1, \infty]$ ,  $(u_n)_{n \in \mathbb{N}} \subset L^p(\Omega)$  and  $u \in L^p(\Omega)$ , such that  $u_n \rightarrow u$  in  $L^p(\Omega)$ , i.e.  $\|u_n - u\|_{L^p(\Omega)} \rightarrow 0$  as  $n \rightarrow \infty$ . Then there is a subsequence  $(u_{n_k})_{k \in \mathbb{N}}$  and a function  $h \in L^p(\Omega)$  such that  $u_{n_k}(x) \rightarrow u(x)$  a.e. in  $\Omega$  as  $k \rightarrow \infty$  and  $|u_{n_k}(x)| \leq h(x)$  a.e. in  $\Omega$  for all  $k \in \mathbb{N}$ .

v) Minkowski's inequality: Let  $1 \leq p \leq \infty$  and  $u, v \in L^p(\Omega)$ . Then

$$\|u + v\|_{L^p(\Omega)} \leq \|u\|_{L^p(\Omega)} + \|v\|_{L^p(\Omega)}.$$

vi) Hölder's inequality: Let  $p, q \in [1, \infty]$  with  $\frac{1}{p} + \frac{1}{q} = 1$  and  $u \in L^p(\Omega), v \in L^q(\Omega)$ . Then  $uv \in L^1(\Omega)$  and

$$\|uv\|_{L^1(\Omega)} \leq \|u\|_{L^p(\Omega)} \|v\|_{L^q(\Omega)}.$$

vii) For  $x, y \in \mathbb{R}^n$ ,

$$\|x\|_p = \left( \sum_{i=1}^n |x_i|^p \right)^{\frac{1}{p}} \quad \text{if } p \in [1, \infty),$$

$$\|x\|_\infty = \max_i |x_i|$$

the discrete versions of v), vi) are valid:

$$\|x + y\|_p \leq \|x\|_p + \|y\|_p,$$

$$|x \cdot y| \leq \|x\|_p \|y\|_q \quad \text{for } p \in [1, \infty], \frac{1}{p} + \frac{1}{q} = 1.$$

viii) General Hölder inequality: Let  $p_k \in [1, \infty], \frac{1}{p_1} + \dots + \frac{1}{p_m} = 1, m \geq 3, u_k \in L^{p_k}(\Omega), k = 1, \dots, m$ . Then

$$\int_{\Omega} |u_1 \cdots u_m| \, dx \leq \prod_{k=1}^m \|u_k\|_{L^{p_k}(\Omega)}.$$

## 2.2 Limit Theorems and Fubini

i) Monotone convergence (Beppo-Levi): Let  $(u_n)_{n \in \mathbb{N}}$  be measurable in  $\Omega$ , non-negative, and point-wise non-decreasing. Then

$$\int_{\Omega} \left( \lim_{n \rightarrow \infty} u_n(x) \right) \, dx = \lim_{n \rightarrow \infty} \int_{\Omega} u_n(x) \, dx.$$

ii) Fatou's lemma: Let  $(u_n)_{n \in \mathbb{N}}$  be measurable in  $\Omega$  and non-negative. Then

$$\int_{\Omega} \left( \liminf_{n \rightarrow \infty} u_n(x) \right) \, dx \leq \liminf_{n \rightarrow \infty} \int_{\Omega} u_n(x) \, dx.$$

iii) Dominated convergence (Lebesgue): Let  $(u_n)_{n \in \mathbb{N}}$  and  $u$  be measurable on  $\Omega$  such that  $u_n(x) \rightarrow u(x)$  as  $n \rightarrow \infty$  a.e. in  $\Omega$  and  $|u_n(x)| \leq h(x)$  a.e. in  $\Omega$  for all  $n \in \mathbb{N}$  and some  $h \in L^1(\Omega)$ . Then  $u_n, u \in L^1(\Omega)$  for all  $n \in \mathbb{N}$  and  $\lim_{n \rightarrow \infty} \int_{\Omega} u_n(x) \, dx = \int_{\Omega} u(x) \, dx$ .

iv) Fubini's theorem: Let  $u = u(x, y)$  be measurable on  $\mathbb{R}^{n+m}$  such that at least one of the following integrals exists and is finite:

$$I_1 = \int_{\mathbb{R}^{n+m}} |u(x, y)| \, dx \, dy,$$

$$I_2 = \int_{\mathbb{R}^m} \left( \int_{\mathbb{R}^n} |u(x, y)| \, dx \right) \, dy,$$

$$I_3 = \int_{\mathbb{R}^n} \left( \int_{\mathbb{R}^m} |u(x, y)| \, dy \right) \, dx.$$

Then  $u(\cdot, y) \in L^1(\mathbb{R}^n)$  for a.e.  $y \in \mathbb{R}^m$ ,  $\int_{\mathbb{R}^m} u(\cdot, y) \, dy \in L^1(\mathbb{R}^n)$ ,  $u(x, \cdot) \in L^1(\mathbb{R}^m)$  for a.e.  $x \in \mathbb{R}^n$ ,  $\int_{\mathbb{R}^n} u(x, \cdot) \, dx \in L^1(\mathbb{R}^m)$ , and  $I_1 = I_2 = I_3$ .

## 2.3 Dense Subspaces and Mollifier

In this section let  $\Omega \subset \mathbb{R}^n$  be open.

i)  $C_0^\infty(\Omega)$  is dense in  $L^p(\Omega)$  for any  $p \in [1, \infty)$ , i.e. for any  $u \in L^p(\Omega)$  and  $\varepsilon > 0$  there is  $\varphi \in C_0^\infty(\Omega)$  such that  $\|\varphi - u\|_{L^p(\Omega)} < \varepsilon$ .

ii) Notation: For  $\varepsilon > 0, x \in \mathbb{R}^n$ , let

$$B_\varepsilon(x) := \{y \in \mathbb{R}^n : |y - x| < \varepsilon\},$$

$$\Omega_\varepsilon := \{x \in \Omega : \text{dist}(x, \partial\Omega) > \varepsilon\}, \quad \text{and}$$

$$L_{\text{loc}}^p(\Omega) := \{u : \Omega \rightarrow [-\infty, \infty] : u \in L^p(V) \text{ for all } V \Subset \Omega\}, \quad \text{for } p \in [1, \infty].$$

iii) Standard mollifier: Let

$$\eta(x) := \begin{cases} c \exp\left(\frac{1}{|x|^2-1}\right), & |x| < 1, \\ 0, & |x| \geq 1, \end{cases}$$

where  $c > 0$  is chosen such that  $\int_{\mathbb{R}^n} \eta(x) dx = 1$ . Then  $\eta \in C_0^\infty(\mathbb{R}^n)$  is called *standard mollifier*. For  $\varepsilon > 0$ ,  $\eta_\varepsilon(x) := \frac{1}{\varepsilon^n} \eta\left(\frac{x}{\varepsilon}\right)$ ,  $x \in \mathbb{R}^n$ , satisfies  $\eta_\varepsilon \in C_0^\infty(\mathbb{R}^n)$ ,  $\int_{\mathbb{R}^n} \eta_\varepsilon(x) dx = 1$ , and  $\text{supp}(\eta_\varepsilon) = \overline{B_\varepsilon(0)}$ .

iv) For  $u \in L^1(\Omega)$ , we extend  $u$  by  $u(x) := 0$  for all  $x \in \mathbb{R}^n \setminus \Omega$  to  $u \in L^1(\mathbb{R}^n)$  and define its *mollification*  $u_\varepsilon := \eta_\varepsilon * u$  for  $\varepsilon > 0$ , i.e.

$$\begin{aligned} u_\varepsilon(x) &= \int_{\mathbb{R}^n} \eta_\varepsilon(x-y)u(y) dy = \int_{\Omega} \eta_\varepsilon(x-y)u(y) dy \\ &= \int_{B_\varepsilon(x) \cap \Omega} \eta_\varepsilon(x-y)u(y) dy, \quad x \in \mathbb{R}^n. \end{aligned}$$

The mollification has the following properties:

**Theorem 2.1.** *Let  $u \in L^1(\Omega)$  and  $\varepsilon > 0$ . Then the following statements hold true:*

a)  $u_\varepsilon \in C^\infty(\mathbb{R}^n)$ ,  $u_\varepsilon(x) \rightarrow u(x)$  as  $\varepsilon \downarrow 0$  for a.e.  $x \in \Omega$ .

b) If  $\text{supp}(u) \Subset \Omega$ , then  $u_\varepsilon \in C_0^\infty(\Omega)$  for small enough  $\varepsilon$ .

c) If  $u \in C^0(\Omega)$ ,  $V \Subset \Omega$ , then  $u_\varepsilon \rightarrow u$  uniformly in  $V$  as  $\varepsilon \downarrow 0$ .

d) If  $u \in L^p(\Omega)$  for some  $p \in [1, \infty)$ , then  $u_\varepsilon \in L^p(\Omega)$ ,  $\|u_\varepsilon\|_{L^p(\Omega)} \leq \|u\|_{L^p(\Omega)}$  and  $u_\varepsilon \rightarrow u$  in  $L^p(\Omega)$  as  $\varepsilon \downarrow 0$ . Moreover,  $u_\varepsilon \in C^\infty(\Omega)$ .

e) If  $u \in L_{\text{loc}}^1(\Omega)$ , then  $u_\varepsilon \in C^\infty(\Omega_\varepsilon)$ .

*Proof.* a) For  $i \in \{1, \dots, n\}$  and  $h \in \mathbb{R} \setminus \{0\}$  let

$$D_i^h v(x) := \frac{1}{h} (v(x + h e_i) - v(x)), \quad x \in \mathbb{R}^n.$$



As  $\eta_\varepsilon \in C_0^\infty(\mathbb{R}^n)$ , we have  $\nabla \eta_\varepsilon \in L^\infty(\mathbb{R}^n)^n$ . So  $D_i^h \eta_\varepsilon \in L^\infty(\mathbb{R}^n)$  by the mean value theorem. As moreover  $D_i^h \eta_\varepsilon(z) \rightarrow \frac{\partial \eta_\varepsilon}{\partial x_i}(z)$  as  $h \rightarrow 0$  for any  $z \in \mathbb{R}^n$ , the dominated convergence theorem implies

$$\begin{aligned} D_i^h(u_\varepsilon)(x) &= \int_{\Omega} \frac{1}{h} (\eta_\varepsilon(x + h e_i - y) - \eta_\varepsilon(x - y)) u(y) \, dy = \int_{\Omega} (D_i^h \eta_\varepsilon(x - y)) u(y) \, dy \\ &\rightarrow \int_{\Omega} \frac{\partial \eta_\varepsilon}{\partial x_i}(x - y) u(y) \, dy \quad \text{as } \varepsilon \downarrow 0. \end{aligned}$$

Hence,  $\frac{\partial}{\partial x_i} u_\varepsilon(x) = \int_{\Omega} \frac{\partial \eta_\varepsilon}{\partial x_i}(x - y) u(y) \, dy$ . By induction,  $u_\varepsilon \in C^\infty(\mathbb{R}^n)$ . By Lebesgue's differentiation theorem (see [Eva10][§E.4]), for a.e.  $x \in \Omega$  we have

$$(2.1) \quad \lim_{r \downarrow 0} \frac{1}{|B_r(x)|} \int_{B_r(x)} |u(y) - u(x)| \, dy = 0.$$

For any such  $x$  we obtain (by choosing  $\varepsilon > 0$  small such that  $\overline{B_\varepsilon(x)} \subset \Omega$ )

$$\begin{aligned} |u_\varepsilon(x) - u(x)| &= \left| \int_{B_\varepsilon(x)} \eta_\varepsilon(x - y) f(y) \, dy \right| = \left| \int_{B_\varepsilon(x)} \eta_\varepsilon(x - y) (f(y) - f(x)) \, dy \right| \\ (2.2) \quad &\leq \frac{1}{\varepsilon^n} \int_{B_\varepsilon(x)} \|\eta\|_{L^\infty(\mathbb{R}^n)} |f(y) - f(x)| \, dy \leq \frac{C}{|B_\varepsilon(x)|} \int_{B_\varepsilon(x)} |f(y) - f(x)| \, dy \\ &\rightarrow 0 \quad \text{as } \varepsilon \downarrow 0 \end{aligned}$$

due to (2.1).

- b) If  $\text{supp}(u) \Subset \Omega$ , let  $\delta := \text{dist}(\text{supp}(u), \partial\Omega) > 0$ . Then for any  $x \in \Omega \setminus \Omega_{\frac{\delta}{2}}$  and  $\varepsilon \leq \frac{\delta}{2}$  we have  $B_\varepsilon(x) \cap \text{supp}(u) = \emptyset$  and

$$u_\varepsilon(x) = \int_{B_\varepsilon(x) \cap \Omega} \eta_\varepsilon(x - y) u(y) \, dy = 0.$$

Hence,  $\text{supp}(u_\varepsilon) \subset \overline{\Omega_{\frac{\delta}{3}}} \Subset \Omega$ . By a),  $u_\varepsilon \in C_0^\infty(\Omega)$ .

- c) For  $u \in C^0(\Omega)$  and  $V \Subset \Omega$ , choose  $W$  such that  $V \Subset W \Subset \Omega$ . Then  $u$  is uniformly continuous in  $W$  and (2.1) holds uniformly for  $x \in V$ . Hence, also (2.2) is satisfied uniformly for  $x \in V$  and  $u_\varepsilon \rightarrow u$  uniformly in  $V$ .

- d) For  $x \in \Omega$ , by using Hölder's inequality and  $\eta_\varepsilon \geq 0$  along with  $\int_{\mathbb{R}^n} \eta_\varepsilon(z) \, dy = 1$ , we get

$$\begin{aligned} |u_\varepsilon(x)| &= \left| \int_{\Omega} (\eta_\varepsilon(x - y))^{1-\frac{1}{p}} (\eta_\varepsilon(x - y))^{\frac{1}{p}} u(y) \, dy \right| \\ &\leq \underbrace{\left( \int_{\Omega} \eta_\varepsilon(x - y) \, dy \right)^{\frac{p-1}{p}}}_{\leq 1} \left( \int_{\Omega} \eta_\varepsilon(x - y) |u(y)|^p \, dy \right)^{\frac{1}{p}} \leq \left( \int_{\Omega} \eta_\varepsilon(x - y) |u(y)|^p \, dy \right)^{\frac{1}{p}}. \end{aligned}$$

Raising this to the power of  $p$  and integrating w.r.t  $x \in \Omega$ , by using Fubini we have

$$\begin{aligned} \|u_\varepsilon\|_{L^p(\Omega)}^p &\leq \int_{\Omega} \int_{\Omega} \eta_\varepsilon(x - y) |u(y)|^p \, dx \, dy = \int_{\Omega} |u(y)|^p \underbrace{\left( \int_{\Omega} \eta_\varepsilon(x - y) \, dx \right)}_{\in [0,1]} \, dy \\ (2.3) \quad &\leq \int_{\Omega} |u(y)|^p \, dy = \|u\|_{L^p(\Omega)}^p. \end{aligned}$$

In particular, this implies  $u_\varepsilon \in L^p(\Omega)$ .

Given  $\mu > 0$ , we may choose  $\varphi \in C_0^\infty(\Omega)$  such that  $\|u - \varphi\|_{L^p(\Omega)} < \frac{\mu}{3}$ . As  $\varphi$  and  $\varphi_\varepsilon$  have compact support in  $\Omega$  by b), we deduce from c) that  $\varphi_\varepsilon \rightarrow \varphi$  uniformly in  $\Omega$  as  $\varepsilon \downarrow 0$ . Hence, we may choose  $\varepsilon_0 > 0$  small enough such that  $\|\varphi_\varepsilon - \varphi\|_{L^p(\Omega)} < \frac{\mu}{3}$  for all  $\varepsilon \in (0, \varepsilon_0)$ . But then,

$$\begin{aligned} \|u_\varepsilon - u\|_{L^p(\Omega)} &\leq \|u_\varepsilon - \varphi_\varepsilon\|_{L^p(\Omega)} + \|\varphi_\varepsilon - \varphi\|_{L^p(\Omega)} + \|\varphi - u\|_{L^p(\Omega)} \\ &\leq \|\eta_\varepsilon * u - \eta_\varepsilon * \varphi\|_{L^p(\Omega)} + \frac{2}{3}\mu \\ &= \|\eta_\varepsilon * (u - \varphi)\|_{L^p(\Omega)} + \frac{2}{3}\mu = \|(u - \varphi)_\varepsilon\|_{L^p(\Omega)} + \frac{2}{3}\mu \\ &\stackrel{(2.3)}{\leq} \|u - \varphi\|_{L^p(\Omega)} + \frac{2}{3}\mu < \mu \quad \text{for all } \varepsilon \in (0, \varepsilon_0). \end{aligned}$$

We still have  $u_\varepsilon \in C^\infty(\Omega)$  since for  $x \in B_\delta(x_0)$  with  $\overline{B_{2\delta}(x_0)} \subset \Omega$  we have for  $x \in K := \overline{B_{2\delta}(x_0)}$  and  $\varepsilon \in (0, \delta)$ ,  $u_\varepsilon(x) = \int_K \eta_\varepsilon(x - y)u(y) dy$ . A similar argument shows e).  $\square$

## 2.4 Polar Coordinates

Let  $f \in C^1(\overline{B_r(x_0)})$  with  $x_0 \in \mathbb{R}^n$ ,  $r > 0$ . Then by the transformation rule with  $x = x_0 + sz$ ,  $s \in (0, r)$ ,  $z \in \partial B_1(0)$  we have

$$\int_{B_r(x_0)} f(x) dx = \int_0^r \left( \int_{\partial B_s(x_0)} f d\sigma(x) \right) ds = \int_0^r s^{n-1} \int_{\partial B_1(0)} f(x_0 + sz) d\sigma(z) ds.$$

In particular, if  $x_0 = 0$ ,  $f$  is radially symmetric and  $\omega_n$  is the surface  $|\partial B_1(0)|$  of  $\partial B_1(0)$ , we get

$$\int_{B_r(0)} f(x) dx = \omega_n \int_0^r f(s) s^{n-1} ds,$$

where  $s = |x|$ .

*Proof.* Appendix in [Eva10].  $\square$

## Chapter 3

# Weak Derivatives and Definitions of Sobolev Spaces

We already saw in the introduction that for  $u \in C^1(\Omega)$  with  $\Omega \subset \mathbb{R}^n$  open we have

$$(3.1) \quad \int_{\Omega} u(x) \varphi_{x_i}(x) \, dx = - \int_{\Omega} u_{x_i}(x) \varphi(x) \, dx \quad \text{for all } \varphi \in C_0^\infty(\Omega).$$

More generally, for higher order derivatives we have the following result:

**Lemma 3.1.** *Let  $\Omega \subset \mathbb{R}^n$  be open,  $u \in C^k(\Omega)$  with  $k \in \mathbb{N}$ , and  $\alpha \in \mathbb{N}_0^n$  be a multiindex with  $|\alpha| = k$ . Then*

$$(3.2) \quad \int_{\Omega} u(x) D^\alpha \varphi(x) \, dx = (-1)^{|\alpha|} \int_{\Omega} D^\alpha u(x) \varphi(x) \, dx \quad \text{for all } \varphi \in C_0^\infty(\Omega).$$

*Proof.* For  $k = 1$ , (3.2) is just (3.1) which was verified in the exercise. For  $\alpha = (\alpha_1, \dots, \alpha_n)$  with  $|\alpha| = k$  we have

$$D^\alpha \phi(x) = \frac{\partial^{\alpha_1}}{\partial x_1^{\alpha_1}} (\dots (\frac{\partial^{\alpha_n}}{\partial x_n^{\alpha_n}}) \dots) \phi(x)$$

and (3.2) follows by applying (3.1)  $k$  times.  $\square$

In order to define the weak derivative  $D^\alpha u$ , we look for a variant of (3.2) which is satisfied if  $u$  has less regularity than being in  $C^k(\Omega)$ . As the integrals in (3.2) are meaningful if  $u, D^\alpha u \in L_{\text{loc}}^1(\Omega)$ , we define the weak derivative  $D^\alpha u$  of  $u$  as follows (see introduction for  $|\alpha| = 1$ ).

**Definition 3.2.** Let  $\Omega$  be an open set,  $u \in L_{\text{loc}}^1(\Omega)$  and  $\alpha \in \mathbb{N}_0^n$  a multiindex.  $u$  has the  $\alpha$ th weak partial derivative  $D^\alpha u$  if there is  $v \in L_{\text{loc}}^1(\Omega)$  such that

$$(3.3) \quad \int_{\Omega} u(x) D^\alpha \varphi(x) \, dx = (-1)^{|\alpha|} \int_{\Omega} v(x) \varphi(x) \, dx \quad \text{for all } \varphi \in C_0^\infty(\Omega).$$

If (3.3) is satisfied, we define  $D^\alpha u := v$ .

In order to show the uniqueness of the weak derivative, we need the following fundamental lemma.

**Lemma 3.3** (Fundamental lemma of calculus of variations). *Let  $\Omega \subset \mathbb{R}^n$  be open and  $u \in L_{\text{loc}}^1(\Omega)$ . Then we have the equivalence*

$$\int_{\Omega} u(x) \varphi(x) \, dx = 0 \quad \text{for all } \varphi \in C_0^\infty(\Omega) \iff u = 0 \text{ a.e. in } \Omega.$$

*Proof.* “ $\Leftarrow$ ” is obvious.

“ $\Rightarrow$ ”: Let  $u \in L^1_{\text{loc}}(\Omega)$  with  $\int_{\Omega} u \varphi \, dx = 0$  for all  $\varphi \in C_0^\infty(\Omega)$ . We fix  $K \subset \Omega$  compact and define

$$\text{sign}(u(x)) := \begin{cases} 1 & \text{if } u(x) > 0, \\ -1 & \text{if } u(x) < 0, \\ 0 & \text{if } u(x) \in \{0, -\infty, +\infty\} \end{cases}$$

and

$$f(x) := \begin{cases} \text{sign}(u(x)) & \text{if } x \in K, \\ 0 & \text{if } x \in \mathbb{R}^n \setminus K. \end{cases}$$

As  $|u| < \infty$  a.e. in  $K$  a.e., we have  $u(x)f(x) = |u(x)|$  for a.e.  $x \in K$ . Since  $f \in L^\infty(\Omega)$  with  $\text{supp}(f) \subset K \Subset \Omega$ , we define  $\varphi_n := f \cdot \eta_{\frac{1}{n}} = \eta_{\frac{1}{n}} * f$  and deduce from Theorem 2.1 a), b) that  $\varphi_n \in C_0^\infty(\Omega)$  and  $\varphi_{n_k}(x) \rightarrow f(x)$  a.e. in  $\Omega$  as  $k \rightarrow \infty$  for some subsequence. As moreover

$$|\varphi_{n_k}(x)| \leq \int_{\Omega} \underbrace{\eta_{\frac{1}{n_k}}(x-y)}_{\leq 1} |f(y)| \, dy \leq \|f\|_{L^\infty(\Omega)} \underbrace{\int_{\Omega} \eta_{\frac{1}{n_k}}(x-y) \, dy}_{\leq 1} \leq 1 \quad \text{for all } x \in \Omega, k \in \mathbb{N},$$

the dominated convergence theorem implies

$$0 = \lim_{k \rightarrow \infty} \int_{\Omega} u(x) \varphi_{n_k}(x) \, dx = \int_{\Omega} u(x) f(x) \, dx = \int_K |u(x)| \, dx.$$

Hence,  $u = 0$  a.e. in  $K$ . As e.g.  $\Omega = \bigcup_{k=1}^{\infty} K_n$  with  $K_n := \overline{\Omega_{\frac{1}{n}}} \cap \overline{B_n(0)}$  and  $u = 0$  a.e. in  $K_n$  (as  $K_n \subset \Omega$  compact), we have  $u = 0$  a.e. in  $\Omega$ .  $\square$

With this result we show the uniqueness of the weak derivative and its equality with the classical derivative if  $u$  is classically differentiable.

**Lemma 3.4.** *Let  $u \in L^1_{\text{loc}}(\Omega)$  and  $\alpha \in \mathbb{N}_0^n$ , with  $|\alpha| = k \in \mathbb{N}$ . If the weak derivative  $D^\alpha u$  exists it is uniquely defined up to a set of measure zero. If  $u \in C^k(\Omega)$ , then  $D^\alpha u$  exists and is equal to the classical derivative  $D^\alpha u$ . Hence, we use  $D^\alpha$  both for weak and classical partial derivatives.*

*Proof.* If  $v$  and  $\tilde{v}$  are  $\alpha$ th weak derivatives of  $u$ , by (3.3)

$$\int_{\Omega} (v - \tilde{v})(x) \varphi(x) \, dx = 0 \quad \text{for all } \varphi \in C_0^\infty(\Omega).$$

Hence, by Lemma 3.3  $v - \tilde{v} = 0$  a.e. in  $\Omega$  and  $v = \tilde{v}$  a.e. in  $\Omega$ . If  $u \in C^k(\Omega)$ , then by Lemma 3.1, (3.3) is satisfied with  $v = D^\alpha u$  and hence the classical derivative  $D^\alpha u$  is also a weak derivative. Due to the uniqueness the claim follows.  $\square$

As the weak derivative is well-defined, we may now define Sobolev spaces consisting of functions having weak derivatives in  $L^p$  spaces.

**Definition 3.5.** a) Let  $k \in \mathbb{N}$ ,  $p \in [1, \infty]$  and  $\Omega \subset \mathbb{R}^n$  be open. We define the Sobolev space

$$W^{k,p}(\Omega) := \left\{ u \in L^p(\Omega) : \text{weak derivative } D^\alpha u \text{ ex. with } D^\alpha u \in L^p(\Omega) \text{ for all } 0 \leq |\alpha| \leq k \right\}$$

with the norm

$$\|u\|_{W^{k,p}(\Omega)} := \begin{cases} \left( \sum_{|\alpha| \leq k} \|D^\alpha u\|_{L^p(\Omega)}^p \right)^{\frac{1}{p}} & \text{if } p \in [1, \infty), \\ \sum_{|\alpha| \leq k} \|D^\alpha u\|_{L^\infty(\Omega)} & \text{if } p = \infty. \end{cases}$$

We further define

$$W_0^{k,p}(\Omega) := \overline{C_0^\infty(\Omega)}^{\|\cdot\|_{W^{k,p}(\Omega)}}$$

to be the closure of  $C_0^\infty(\Omega)$  in  $W^{k,p}(\Omega)$  and

$$W_{\text{loc}}^{k,p}(\Omega) := \bigcap_{V \in \Omega} W^{k,p}(V).$$

For  $p = 2$ , we define  $H^k(\Omega) := W^{k,2}(\Omega)$  and  $H_0^k(\Omega) := W_0^{k,2}(\Omega)$ .

b) For  $(u_m)_{m \in \mathbb{N}} \subset W^{k,p}(\Omega)$  and  $u \in W^{k,p}(\Omega)$ , we say  $u_m \rightarrow u$  in  $W^{k,p}(\Omega)$  if

$$\lim_{n \rightarrow \infty} \|u_m - u\|_{W^{k,p}(\Omega)} = 0.$$

We say  $u_m \rightarrow u$  in  $W_{\text{loc}}^{k,p}(\Omega)$  if  $u_m \rightarrow u$  in  $W^{k,p}(V)$  for all  $V \in \Omega$ .

*Remark 3.6.* a) For  $\alpha = (0, \dots, 0)$  we set  $D^\alpha u = D^0 u = u$ . We further identify functions in  $W^{k,p}(\Omega)$  which agree a.e. If for  $u \in W^{k,p}(\Omega)$  the equivalence class  $[u]$  contains a continuous representative, the latter is chosen for  $u$ .

b)  $u \in W_0^{k,p}(\Omega)$  if and only if there exists  $(u_m)_{m \in \mathbb{N}} \subset C_0^\infty(\Omega)$  such that  $u_m \rightarrow u$  in  $W^{k,p}(\Omega)$ . We interpret  $W_0^{k,p}(\Omega)$  as the set of  $u \in W^{k,p}(\Omega)$  such that “ $D^\alpha u = 0$  on  $\partial\Omega$  for any  $|\alpha| \leq k-1$ ”. This interpretation will be made precise in Chapter 5.

c) The letter “H” in  $H^k(\Omega)$  and  $H_0^k(\Omega)$  is used as those are Hilbert spaces as we will see soon.

**Example 3.7.** Let  $\Omega = B_1(0) \subset \mathbb{R}^n$ ,  $u(x) = |x|^{-a}$  for  $x \in \Omega \setminus \{0\}$  with some  $a > 0$ . Given  $p \in [1, \infty)$ , for which  $a$  do we have  $u \in W^{1,p}(\Omega)$ ?

Since  $u \in C^\infty(\Omega \setminus \{0\})$ , we have for  $x \neq 0$

$$u_{x_i}(x) = -a|x|^{-a-1} \frac{x_i}{|x|} = -\frac{ax_i}{|x|^{a+2}} \quad \text{and} \\ |\nabla u(x)| = \frac{a}{|x|^{a+1}}.$$

For fixed  $\varphi \in C_0^\infty(\Omega)$  and  $\varepsilon > 0$ , Green’s formula ( $\nu$  is the outward unit normal on  $\Omega \setminus \overline{B_\varepsilon(0)}$ ) implies

$$(3.4) \quad \int_{\Omega \setminus \overline{B_\varepsilon(0)}} u \varphi_{x_i} dx = - \int_{\Omega \setminus \overline{B_\varepsilon(0)}} u_{x_i} \varphi dx + \underbrace{\int_{\partial\Omega} u \varphi \nu_i d\sigma}_{=0} + \int_{\partial B_\varepsilon(0)} u \varphi \nu_i d\sigma.$$

We may pass to the limit  $\varepsilon \downarrow 0$  in the first two integrals if  $u \in L^1(\Omega)$  and  $\nabla u \in L^1(\Omega)^n$ , i.e.  $a < n$  and  $a+1 < n$ . As for  $a < n-1$ , we further have

$$\left| \int_{\partial B_\varepsilon(0)} u \varphi \nu_i d\sigma \right| \leq \|\varphi\|_{L^\infty(\Omega)} \int_{\partial B_\varepsilon(0)} \varepsilon^{-a} d\sigma \leq C \varepsilon^{k-1-a} \rightarrow 0 \quad \text{as } \varepsilon \downarrow 0.$$

Hence, for  $a < n-1$  we may pass to the limit  $\varepsilon \downarrow 0$  in (3.4) and obtain  $\int_{\Omega} u \varphi_{x_i} dx = - \int_{\Omega} u_{x_i} \varphi dx$ . Hence, the weak derivative  $u_{x_i}$  exists for  $a < n-1$ . Hence,  $u \in W^{1,p}(\Omega)$  if  $u \in L^p(\Omega)$  and  $\nabla u = \frac{-ax}{|x|^{a+2}} \in L^p(\Omega)^n$ , i.e.  $ap < p$  and  $(a+1)p < n$ . We conclude that

$$u \in W^{1,p}(\Omega) \iff a < \frac{n-p}{p} \text{ (and } p < n\text{)}.$$

Next, we prove some elementary properties of weak derivatives which are well known in the case of classical derivatives.

**Proposition 3.8.** *Let  $\Omega$  be open,  $k \in \mathbb{N}, p \in [1, \infty]$ ,  $u, v \in W^{k,p}(\Omega)$ , and  $\alpha \in \mathbb{N}_0^n$  with  $1 \leq |\alpha| \leq k$ .*

- a)  $D^\alpha u \in W^{k-|\alpha|,p}(\Omega)$  (with  $W^{0,p}(\Omega) = L^p(\Omega)$ ) and  $D^\beta(D^\alpha(u)) = D^\alpha(D^\beta(u)) = D^{\alpha+\beta}(u)$  for all  $\alpha, \beta \in \mathbb{N}_0^n$  with  $|\alpha| + |\beta| \leq k$ .
- b) For  $\lambda, \mu \in \mathbb{R}$  we have  $\lambda u + \mu v \in W^{k,p}(\Omega)$  and  $D^\alpha(\lambda u + \mu v) = \lambda D^\alpha u + \mu D^\alpha v$ .
- c) If  $V \subset \Omega$  is open, then  $u \in W^{k,p}(V)$ .
- d) If  $\xi \in C_0^\infty(\Omega)$ , then  $\xi u \in W^{k,p}(\Omega)$  and Leibniz's formula

$$D^\alpha(\xi u) = \sum_{\beta \leq \alpha} \binom{\alpha}{\beta} D^\beta \xi D^{\alpha-\beta} u$$

holds with

$$\binom{\alpha}{\beta} = \frac{\alpha!}{(\alpha-\beta)! \beta!}, \quad \alpha! = \prod_{i=1}^n \alpha_i!$$

and

$$\beta \leq \alpha \iff \forall i \in \{1, \dots, n\}: \beta_i \leq \alpha_i.$$

*Proof.* b) and c) easily follow from Definition 3.2.

- a) Let  $\varphi \in C_0^\infty(\Omega)$ . Then  $D^\beta \varphi \in C_0^\infty(\Omega)$  and (3.3) implies

$$\begin{aligned} \int_{\Omega} D^\alpha u D^\beta \varphi dx &= (-1)^{|\alpha|} \int_{\Omega} u D^{\alpha+\beta} \varphi dx \\ &= (-1)^{|\alpha|} (-1)^{|\alpha|+|\beta|} \int_{\Omega} D^{\alpha+\beta} u \varphi dx \\ &= (-1)^{|\beta|} \int_{\Omega} D^{\alpha+\beta} u \varphi dx \end{aligned}$$

as  $|\alpha| + |\beta| = |\alpha + \beta|$ . Hence,  $D^\beta(D^\alpha u) = D^{\alpha+\beta} u$ , for  $|\beta| \leq k - |\alpha|$ .

- d) Let  $\varphi \in C_0^\infty(\Omega)$ . In case of  $|\alpha| = 1$ , we have

$$\int_{\Omega} \xi u D^\alpha \varphi dx = \int_{\Omega} (u D^\alpha(\xi \varphi) - u(D^\alpha \xi) \varphi) dx \stackrel{(3.3)}{=} - \int_{\Omega} (\xi D^\alpha u + u D^\alpha \xi) \varphi dx.$$

Hence,  $D^\alpha(\xi u) = \xi D^\alpha u + u D^\alpha \xi \in L^p(\Omega)$  and the claim is true for  $|\alpha| = 1$ .

Assume the claim is true for all  $|\alpha| \leq l$  with some  $l \in \{1, \dots, k-1\}$  (IA).

Let  $\alpha$  satisfy  $|\alpha| = l + 1$ . Then  $\alpha = \beta + \gamma$  for some  $\beta, \gamma \in \mathbb{N}_0^k$  with  $|\beta| = l$  and  $|\gamma| = 1$ . Hence,

$$\begin{aligned}
\int_{\Omega} \xi u D^{\alpha} \varphi &= \int_{\Omega} \xi u D^{\beta} (D^{\gamma} \varphi) dx \\
&\stackrel{(IA)}{=} (-1)^{|\beta|} \int_{\Omega} \sum_{\sigma \leq \beta} \binom{\beta}{\sigma} D^{\sigma} \xi D^{\beta-\sigma} u D^{\gamma} \varphi dx \\
&\stackrel{(3.3)}{=} (-1)^{|\beta|+|\gamma|} \int_{\Omega} \sum_{\sigma \leq \beta} \binom{\beta}{\sigma} D^{\gamma} (D^{\sigma} \xi D^{\beta-\sigma} u) \varphi dx \\
&\stackrel{(IA)}{=} (-1)^{|\alpha|} \int_{\Omega} \sum_{\sigma \leq \beta} \binom{\beta}{\sigma} [D^{\sigma+\gamma} \xi D^{\beta-\sigma} u + D^{\sigma} \xi D^{\alpha-\sigma} u] \varphi dx \\
&= (-1)^{|\alpha|} \int_{\Omega} \sum_{\sigma \leq \beta} \binom{\beta}{\sigma} [D^{\sigma+\gamma} \xi D^{\alpha-(\sigma+\gamma)} u + D^{\sigma} \xi D^{\alpha-\sigma} u] \varphi dx \\
&= (-1)^{|\alpha|} \int_{\Omega} \left[ \sum_{\gamma \leq \rho \leq \alpha} \binom{\beta}{\rho-\gamma} + \sum_{0 \leq \rho \leq \beta} \binom{\beta}{\rho} \right] D^{\rho} \xi D^{\alpha-\rho} u \varphi dx \\
&= (-1)^{|\alpha|} \int_{\Omega} \sum_{\rho \leq \alpha} \left[ \binom{\beta}{\rho-\gamma} + \binom{\beta}{\rho} \right] D^{\rho} \xi D^{\alpha-\rho} u \varphi dx
\end{aligned}$$

with the convention  $\binom{\beta}{\tilde{\beta}} = 0$  if  $\beta_i < \tilde{\beta}_i$  or  $\tilde{\beta}_i < 0$  for some  $i \in \{1, \dots, n\}$ . As

$$\binom{\beta}{\rho-\gamma} + \binom{\beta}{\rho} = \binom{\beta+\gamma}{\rho} = \binom{\alpha}{\rho},$$

we deduce that the claim holds by induction.  $\square$

Finally, we show that  $W^{k,p}(\Omega)$  is a Banach space.

**Theorem 3.9.** *Let  $\Omega \subset \mathbb{R}^n$  be open,  $k \in \mathbb{N}$ ,  $p \in [1, \infty]$ . Then  $W^{k,p}(\Omega)$  is a Banach space. Moreover,  $H^k(\Omega)$  is a Hilbert space with the scalar product*

$$(u, v)_{H^k(\Omega)} := \sum_{|\alpha| \leq k} \int_{\Omega} D^{\alpha} u \overline{D^{\alpha} v} dx.$$

*Proof.* By Proposition 3.8 b),  $W^{k,p}(\Omega)$  is a vector space. For  $p \in [1, \infty)$  and  $u, v \in W^{k,p}(\Omega)$ , Minkowski's inequality (see 2.1) on  $L^p(\Omega)$  and for  $\|\cdot\|_p$  on  $\mathbb{R}^m$  implies

$$\begin{aligned}
\|u + v\|_{W^{k,p}(\Omega)} &= \left( \sum_{|\alpha| \leq k} \|D^{\alpha} u + D^{\alpha} v\|_{L^p(\Omega)}^p \right)^{\frac{1}{p}} \leq \left( \sum_{|\alpha| \leq k} (\|D^{\alpha} u\|_{L^p(\Omega)} + \|D^{\alpha} v\|_{L^p(\Omega)})^p \right)^{\frac{1}{p}} \\
&\leq \left( \sum_{|\alpha| \leq k} \|D^{\alpha} u\|_{L^p(\Omega)}^p \right)^{\frac{1}{p}} + \left( \sum_{|\alpha| \leq k} \|D^{\alpha} v\|_{L^p(\Omega)}^p \right)^{\frac{1}{p}} = \|u\|_{W^{k,p}(\Omega)} + \|v\|_{W^{k,p}(\Omega)}.
\end{aligned}$$

All other properties of the norm are easily verified for  $\|\cdot\|_{W^{k,p}(\Omega)}$ .

Let  $(u_m)_{m \in \mathbb{N}}$  be a Cauchy sequence in  $W^{k,p}(\Omega)$ . Then for all  $|\alpha| \leq k$ ,  $(D^{\alpha} u_m)_{m \in \mathbb{N}}$  is a Cauchy sequence in  $L^p(\Omega)$  as  $\|D^{\alpha} u_m - D^{\alpha} u_l\|_{L^p(\Omega)} \leq \|u_m - u_l\|_{W^{k,p}(\Omega)}$ . Hence, there exists  $u_{\alpha} \in L^p(\Omega)$  with

$$(3.5) \quad D^{\alpha} u_m \rightarrow u_{\alpha} \text{ in } L^p(\Omega), |\alpha| \leq k.$$

For  $\alpha = (0, \dots, 0)$  we define  $u_{(0, \dots, 0)} =: u$  and have

$$(3.6) \quad u_m \rightarrow u \text{ in } L^p(\Omega).$$

To show that  $u_\alpha = D^\alpha u$ , we fix  $\varphi \in C_0^\infty(\Omega)$  and obtain

$$\int_{\Omega} u D^\alpha \varphi \, dx \stackrel{(3.6)}{=} \lim_{m \rightarrow \infty} \int_{\Omega} u_m D^\alpha \varphi \, dx = \lim_{m \rightarrow \infty} (-1)^{|\alpha|} \int_{\Omega} D^\alpha u_m \varphi \, dx \stackrel{(3.5)}{=} (-1)^{|\alpha|} \int_{\Omega} u_\alpha \varphi \, dx$$

since  $\varphi, D^\alpha \varphi \in L^q(\Omega)$  with  $\frac{1}{p} + \frac{1}{q} = 1$ . Hence,  $D^\alpha u = u_\alpha \in L^p(\Omega)$  for all  $|\alpha| \leq k$  and  $u \in W^{k,p}(\Omega)$ . But then (3.5) and (3.6) imply  $u_m \rightarrow u$  in  $W^{k,p}(\Omega)$ . Hence,  $W^{k,p}(\Omega)$  is complete and a Banach space.

That  $(\cdot, \cdot)_{H^k(\Omega)}$  is a scalar product on  $H^k(\Omega)$  easily follows from the  $L^2$ -scalar product. Hence,  $H^k(\Omega)$  is a Hilbert space.  $\square$

In particular,  $W_0^{k,p}(\Omega)$  is a Banach space and a subspace of  $W^{k,p}(\Omega)$ .



## Chapter 4

# Approximation by Smooth Functions

As it is often complicated to use the definition of weak derivatives for proving properties of Sobolev spaces, we aim to approximate functions in Sobolev spaces by smooth functions.

### 4.1 Interior Approximation

We prove that mollification from 2.3 provides approximating functions in  $W_{\text{loc}}^{k,p}(\Omega)$ .

**Theorem 4.1.** *Let  $\Omega \subseteq \mathbb{R}^n$  be open,  $k \in \mathbb{N}$ ,  $p \in [1, \infty)$ , and  $u \in W^{k,p}(\Omega)$ . Then the following statements hold:*

- a)  $u_\varepsilon \in C^\infty(\Omega)$  and  $D^\alpha(u_\varepsilon)(x) = (D^\alpha u)_\varepsilon(x)$  for all  $x \in \Omega_\varepsilon$  and all  $\alpha \in \mathbb{N}_0^n$  with  $|\alpha| \leq k$ .
- b)  $u_\varepsilon \rightarrow u$  in  $W_{\text{loc}}^{k,p}(\Omega)$  as  $\varepsilon \downarrow 0$ .

*Proof.* a) By Theorem 2.1, we have  $u_\varepsilon \in C^\infty(\Omega)$  and for  $|\alpha| \leq k$

$$D^\alpha(u_\varepsilon)(x) = \int_{\Omega} D_x^\alpha \eta_\varepsilon(x-y) u(y) \, dy, \quad x \in \Omega,$$

see proof of Theorem 2.1 a), d). For fixed  $x \in \Omega_\varepsilon$ ,  $\phi(y) := \eta_\varepsilon(x-y)$  satisfies  $\phi \in C_0^\infty(\Omega)$  since  $\text{supp } \phi = \overline{B_\varepsilon(x)}$  and therefore

$$\begin{aligned} D^\alpha(u_\varepsilon)(x) &= (-1)^{|\alpha|} \int_{\Omega} D_y^\alpha (\eta_\varepsilon(x-y)) u(y) \, dy = (-1)^{|\alpha|} \int_{\Omega} D^\alpha \phi(y) u(y) \, dy \\ &\stackrel{(3.3)}{=} (-1)^{|\alpha|+|\alpha|} \int_{\Omega} \phi(y) D^\alpha u(y) \, dy = \int_{\Omega} \eta_\varepsilon(x-y) D^\alpha u(y) \, dy = (D^\alpha u)_\varepsilon(x). \end{aligned}$$

Since  $x \in \Omega_\varepsilon$  was arbitrary, this proves a).

- b) In view of a) and Theorem 2.1 d), for fixed  $V \Subset \Omega$  we have  $D^\alpha u_\varepsilon = \eta_\varepsilon * D^\alpha u$  in  $V$  for  $\varepsilon \in (0, \varepsilon_0)$ , as  $V \subset \Omega_\varepsilon$  for  $\varepsilon$  small enough so that  $D^\alpha u_\varepsilon \rightarrow D^\alpha u$  in  $L^p(V)$  as  $\varepsilon \downarrow 0$  for any  $\alpha \in \mathbb{N}_0^n, |\alpha| \leq k$ . Then

$$\|u_\varepsilon - u\|_{W^{k,p}(V)}^p = \sum_{|\alpha| \leq k} \|D^\alpha u_\varepsilon - D^\alpha u\|_{L^p(V)}^p \rightarrow 0 \quad \text{as } \varepsilon \downarrow 0. \quad \square$$

## 4.2 Approximation by Smooth Functions

In order to show that for any  $u \in W^{k,p}(\Omega)$  there is  $(u_m)_{m \in \mathbb{N}} \subset C^\infty(\Omega) \cap W^{k,p}(\Omega)$  such that  $u_m \rightarrow u$  in  $W^{k,p}(\Omega)$  (and not only in  $W_{\text{loc}}^{k,p}(\Omega)$ ), we need the following lemmas to construct a partition of unity.

**Lemma 4.2.** *Let  $\Omega \subset \mathbb{R}^n$  be open and  $K \subset \Omega$  compact. If  $\text{dist}(K, \partial\Omega) \geq \delta > 0$ , then there exists a cutoff-function  $\tau \in C_0^\infty(\Omega)$  w.r.t.  $K, \Omega$  with  $0 \leq \tau \leq 1$ ,  $\tau = 1$  in  $K$ , and*

$$|D^\alpha \tau(x)| \leq c\delta^{-k} \quad \text{for all } x \in \Omega \setminus K, k \in \mathbb{N}, |\alpha| = k,$$

where  $c > 0$  depends on  $k$  and  $n$  but not on  $\Omega$  or  $K$ .

*Proof.* We may choose  $\delta > 0$  since  $K$  is compact. Hence,

$$\tilde{K} := \overline{\bigcup_{x \in K} B_{\frac{\delta}{2}}(x)}$$

is compact with  $\text{dist}(\partial\tilde{K}, \partial K) = \frac{\delta}{2} \leq \text{dist}(\delta\tilde{K}, \partial\Omega)$ .

As  $\chi_{\tilde{K}} \in L^1(\Omega)$  with  $\text{supp } \chi_{\tilde{K}} = \tilde{K} \Subset \Omega$ , we have that  $\tau := \eta_{\frac{\delta}{4}} * \chi_{\tilde{K}}$  satisfies  $\tau \in C_0^\infty(\Omega)$ ,  $0 \leq \tau \leq 1$ , and  $\tau = 1$  in  $K$  by Theorem 2.1, as

$$\tau(x) = \int_{B_{\frac{\delta}{4}}(x)} \eta_{\frac{\delta}{4}}(x-y) \underbrace{\chi_{\tilde{K}}(y)}_{=1} dy = 1 \quad \text{for all } x \in K$$

since  $B_{\frac{\delta}{4}}(x) \subset \tilde{K}$ . Moreover, for  $|\alpha| = k$

$$D^\alpha \eta_{\frac{\delta}{4}}(x) = \left(\frac{4}{\delta}\right)^n D^\alpha \left[ \eta\left(\frac{4}{\delta}x\right) \right] = \left(\frac{4}{\delta}\right)^{n+k} (D^\alpha \eta)\left(\frac{4}{\delta}x\right).$$

Hence, for  $x \in \Omega \setminus K$  we have

$$|D^\alpha \tau(x)| \leq \int_{B_{\frac{\delta}{4}}(x)} \left(\frac{4}{\delta}\right)^{n+k} \|D^\alpha \eta\|_{L^\infty(\mathbb{R}^n)} \chi_{\tilde{K}}(y) dy \leq \tilde{c}(n, k) \delta^{-n-k} |B_{\frac{\delta}{4}}(x)| \leq c(n, k) \delta^{-k}$$

which concludes the proof.  $\square$

**Lemma 4.3** (Partition of unity). *Let  $K \subset \mathbb{R}^n$  be compact and  $\{\Omega_k\}_{k=1, \dots, N}$  be an open covering of  $K$ . Then, there exist  $\psi_k, k = 1, \dots, N$ , called partition of unity such that  $\psi_k \in C_0^\infty(\Omega_k)$ ,  $0 \leq \psi_k \leq 1$  in  $\Omega_k$ , and  $\sum_{k=1}^N \psi_k(x) = 1$  for all  $x \in K$ .*

*Proof.* For any  $x \in K$  there is  $r = r(x) > 0$  and  $1 \leq k \leq N$  such that  $B_{x,k} := B_r(x) \Subset \Omega_k$ . Hence,

$$\{B_{x,k}\}_{\substack{x \in K \cap \Omega_k, \\ k=1, \dots, N}}$$

is an open covering of  $K$  and has a finite subset still covering  $K$ , called

$$\{B_i^k\}_{\substack{i=1, \dots, N_k, \\ k=1, \dots, N}}$$

Then

$$K_k := \overline{\bigcup_{i=1}^{N_k} B_i^k}$$

satisfies  $K_k \Subset \Omega_k$  and  $\bigcup_{k=1}^N K_k \supset K$ . Let  $\tilde{\psi}_k$  denote the cutoff-function w.r.t  $K_k, \Omega_k$ . Hence,  $\tilde{\psi}_k \in C_0^\infty(\Omega_k)$  satisfies  $0 \leq \tilde{\psi}_k \leq 1$  and

$$\psi(x) := \sum_{k=1}^N \tilde{\psi}_k(x) \geq 1 \quad \text{for all } x \in K.$$

Furthermore, we have

$$K \Subset \Omega := \bigcup_{k=1}^N \text{supp}(\tilde{\psi}_k)$$

and there is an open set  $\Omega_0$  such that  $K \subset \Omega_0 \Subset \Omega$ . Let  $\tau$  be a cutoff-function w.r.t  $K, \Omega_0$  and

$$\psi_k(x) := \begin{cases} \frac{\tilde{\psi}_k(x)\tau(x)}{\psi(x)} & \text{if } x \in \Omega_0, \\ 0 & \text{if } x \notin \Omega_0. \end{cases}$$

Then  $\psi_1, \dots, \psi_N$  have the claimed properties.  $\square$

Now we prove the announced result that  $C^\infty(\Omega) \cap W^{k,p}(\Omega)$  is dense in  $W^{k,p}(\Omega)$  without assuming any smoothness of  $\partial\Omega$ .

**Theorem 4.4** (Meyers and Serrin). *Let  $\Omega \subset \mathbb{R}^n$  be open,  $k \in \mathbb{N}$ , and  $p \in [1, \infty)$ . Then  $C^\infty(\Omega) \cap W^{k,p}(\Omega)$  is dense in  $W^{k,p}(\Omega)$ , i.e. for any  $u \in W^{k,p}(\Omega)$  there exists  $(u_m)_{m \in \mathbb{N}} \subset C^\infty(\Omega) \cap W^{k,p}(\Omega)$  such that  $u_m \rightarrow u$  in  $W^{k,p}(\Omega)$  as  $m \rightarrow \infty$ .*

*Proof.* i) With

$$U_i := \{x \in \Omega : \text{dist}(x, \partial\Omega) > \frac{1}{i} \text{ and } |x| < i\}, \quad i \in \mathbb{N},$$

we have  $\bigcup_{i=1}^\infty U_i = \Omega$  and  $U_i \subset U_{i+1}$ . Moreover,

$$V_i := U_{i+4} \setminus \overline{U_{i+1}}, i \in \mathbb{N}, \quad \text{and} \quad V_0 := U_4$$

are all open with  $V_i \Subset \Omega$  for all  $i \in \mathbb{N}_0$  and  $\Omega = \bigcup_{i=0}^\infty V_i$ . Defining further

$$W_i := \overline{U_{i+3}} \setminus U_{i+2}, i \in \mathbb{N}, \quad \text{and} \quad W_0 := \overline{U_3},$$

all  $W_i \subset V_i$  are compact and we have  $\Omega = \bigcup_{i=0}^\infty W_i$ . Let  $\psi_i \in C_0^\infty(V_i)$  denote a cutoff-function w.r.t.  $W_i, V_i$  with  $0 \leq \psi_i \leq 1$  and  $\psi_i = 1$  in  $W_i$  for  $i \in \mathbb{N}_0$ . Since for all  $j \geq i+2$

$$W_i \cap V_j = \left( \overline{U_{i+3}} \cap \overline{U_{j+1}}^c \right) \cap (U_{i+2}^c \cap U_{j+4}) = \emptyset,$$

and for all  $j \geq i+3$ ,  $V_i \cap V_j = \emptyset$ , for any  $x \in \Omega$  we have

$$\sigma(x) := \sum_{i=0}^\infty \psi_i(x) > 0$$

and only finitely many of the  $\psi_i(x)$  are non-zero. Hence,  $\{\xi_i\}_{i=0}^\infty$ , defined by

$$\xi_i(x) := \frac{\psi_i(x)}{\sigma(x)}, \quad x \in \Omega,$$

is a *partition of unity subordinate to*  $\{V_i\}_{i=0}^\infty$ , i.e.  $\xi_i \in C_0^\infty(V_i)$ ,  $0 \leq \xi_i \leq 1$ , and  $\sum_{i=0}^\infty \xi_i = 1$  in  $\Omega$  and for any  $K \Subset \Omega$ ,  $\xi_i|_K \not\equiv 0$  only for finitely many  $i$ .

ii) Let  $u \in W^{k,p}(\Omega)$  be arbitrary. Then by Proposition 3.8 d) and i) we have  $\xi_i u \in W^{k,p}(\Omega)$  and  $\text{supp}(\xi_i u) \subset V_i$  for all  $i \in \mathbb{N}_0$ . We fix  $\delta > 0$ . Then for any  $i \in \mathbb{N}_0$  we define

$$Z_i := U_{i+5} \setminus \overline{U_i} \supset V_i, i \in \mathbb{N}, \quad \text{and} \quad Z_0 := U_5 \supset V_0.$$

In view of Theorem 4.1, there is  $\varepsilon_i > 0$  small enough such that  $u_i := \eta_{\varepsilon_i} * (\xi_i u)$  satisfies  $u_i \in C_0^\infty(Z_i)$  and

$$(4.1) \quad \|u_i - \xi_i u\|_{W^{k,p}(\Omega)} = \|u_i - \xi_i u\|_{W^{k,p}(Z_i)} \leq \frac{\delta}{2^{i+1}}$$

for  $i \in \mathbb{N}_0$  as  $u_i - \xi_i u \equiv 0$  in  $\Omega \setminus Z_i$ . Define

$$v(x) := \sum_{i=0}^{\infty} u_i(x), \quad x \in \Omega.$$

Then for any open set  $V \Subset \Omega$  only finitely many  $u_i$  satisfy  $u_i|_V \neq 0$ . Since  $u = \sum_{i=0}^{\infty} \xi_i u$ , we obtain  $v \in C^\infty(\Omega)$  and

$$\|v - u\|_{W^{k,p}(V)} \leq \sum_{i=0}^{\infty} \|u_i - \xi_i u\|_{W^{k,p}(V)} \stackrel{(4.1)}{\leq} \delta \sum_{i=0}^{\infty} \frac{1}{2^{i+1}} = \delta \quad \text{for all } V \Subset \Omega.$$

Since  $U_i \subset U_{i+1}$  for all  $i \in \mathbb{N}$ ,  $U_i \Subset \Omega$ , and  $\Omega = \bigcup_{i=1}^{\infty} U_i$ , we conclude by the monotone convergence theorem

$$\|v - u\|_{W^{k,p}(\Omega)}^p = \sum_{|\alpha| \leq k} \|D^\alpha(v - u)\|_{L^p(\Omega)}^p = \lim_{i \rightarrow \infty} \sum_{|\alpha| \leq k} \|D^\alpha(v - u)\|_{L^p(U_i)}^p \leq \delta^p.$$

As  $\delta > 0$  was arbitrary, the claim is proved.  $\square$

*Remark 4.5.* Historically, there were two definitions of Sobolev spaces.  $W^{k,p}(\Omega)$  was defined as in Definition 3.5 while  $H^{k,p}(\Omega)$  was defined as the closure of  $C^\infty(\Omega) \cap W^{k,p}(\Omega)$  w.r.t  $\|\cdot\|_{W^{k,p}(\Omega)}$ . Obviously  $H^{k,p}(\Omega) \subseteq W^{k,p}(\Omega)$  but only after Meyers and Serrin in 1964 [MS64] it was clear that  $H^{k,p}(\Omega) \supseteq W^{k,p}(\Omega)$  without assuming any smoothness condition of  $\partial\Omega$ .

We can now prove the chain rule for  $W^{1,p}(\Omega)$  functions.

**Proposition 4.6.** *Let  $\Omega$  be open,  $p \in [1, \infty)$ , and  $f \in C^1(\mathbb{R})$  such that  $|f'| \leq M$  on  $\mathbb{R}$  for some  $M > 0$ . Assume further that  $f(0) = 0$  or  $|\Omega| < \infty$  is satisfied. Then for any  $u \in W^{1,p}(\Omega)$  we have  $f(u)$  in  $W^{1,p}(\Omega)$  with*

$$\nabla f(u) = f'(u) \nabla u.$$

*Proof.* As  $f'$  is continuous and bounded and  $u$  is measurable, we have  $f'(u) \in L^\infty(\Omega)$  and  $f'(u) \nabla u \in L^p(\Omega)$ . In view of

$$|f(x)| \leq |f(0)| + M|x| \quad \text{for all } x \in \mathbb{R},$$

the assumption  $f(0) = 0$  or  $|\Omega| < \infty$  implies  $f(u) \in L^p(\Omega)$ . By Theorem 4.4, there exists  $(u_m)_{m \in \mathbb{N}} \subset C^\infty(\Omega) \cap W^{1,p}(\Omega)$  such that  $u_m \rightarrow u$  in  $W^{1,p}(\Omega)$  and  $u_m \rightarrow u$  a.e. in  $\Omega$ . Hence,

$u_m \rightarrow u$  and  $(u_m)_{x_i} \rightarrow u_{x_i}$  in  $L^p(\Omega)$  for all  $i \in \{1, \dots, n\}$ . We fix  $i \in \{1, \dots, n\}$  and  $\varphi \in C_0^\infty(\Omega)$ . In view of  $f(u_m) \in C^1(\Omega)$ , we deduce from (3.2)

$$(4.2) \quad \int_{\Omega} f(u_m) \varphi_{x_i} dx = - \int_{\Omega} f'(u_m) (u_m)_{x_i} \varphi dx \quad \text{for all } m \in \mathbb{N},$$

by the classical chain rule. On the one hand, for  $q \in [1, \infty]$  with  $\frac{1}{p} + \frac{1}{q} = 1$  we have by Hölder's inequality

$$\begin{aligned} \left| \int_{\Omega} (f(u_m) - f(u)) \varphi_{x_i} dx \right| &\leq M \int_{\Omega} |u_m - u| |\varphi_{x_i}| dx \\ &\leq M \|u_m - u\|_{L^p(\Omega)} \|\varphi_{x_i}\|_{L^q(\Omega)} \rightarrow 0 \quad \text{as } m \rightarrow \infty \end{aligned}$$

since  $f$  is Lipschitz. On the other hand,

$$|f'(u_m) - f'(u)| |u_{x_i}| |\varphi| \leq 2M |u_{x_i}| \|\varphi\|_{L^\infty(\Omega)} \in L^1(\text{supp}(\varphi))$$

as  $\text{supp}(\varphi)$  is bounded and thus

$$\begin{aligned} &\left| \int_{\Omega} (f'(u_m) (u_m)_{x_i} - f'(u) u_{x_i}) \varphi dx \right| \\ &\leq \int_{\Omega} |f'(u_m)| |(u_m)_{x_i} - u_{x_i}| |\varphi| dx + \int_{\Omega} |f'(u_m) - f'(u)| |u_{x_i}| |\varphi| dx \\ &\leq M \|(u_m)_{x_i} - u_{x_i}\|_{L^p(\Omega)} \|\varphi\|_{L^q(\Omega)} + \int_{\text{supp}(\varphi)} |f'(u_m) - f'(u)| |u_{x_i}| |\varphi| dx. \\ &\rightarrow 0 \quad \text{as } m \rightarrow \infty \end{aligned}$$

by the dominated convergence theorem.

Hence, letting  $m \rightarrow \infty$  in (4.2) we conclude that  $(f(u))_{x_i} = f'(u) u_{x_i}$  in the weak sense.  $\square$

Unlike for classical derivatives, now  $u \in W^{1,p}(\Omega)$  implies  $|u| \in W^{1,p}(\Omega)$ .

**Corollary 4.7.** *Let  $\Omega \subset \mathbb{R}^n$  be open,  $p \in [1, \infty)$ , and  $u \in W^{1,p}(\Omega)$ . Define*

$$u_+(x) := \max\{u(x), 0\} \quad \text{and} \quad u_-(x) = \max\{-u(x), 0\}.$$

*Then  $u_+, u_-, |u| \in W^{1,p}(\Omega)$  with  $\nabla u_+(x) = \nabla u(x) \chi_{\{u>0\}}(x)$ ,  $\nabla u_-(x) = -\nabla u(x) \chi_{\{u<0\}}(x)$ , and  $\nabla |u|(x) = \nabla u(x) (\chi_{\{u>0\}}(x) - \chi_{\{u<0\}}(x))$ .*

*Proof.* Exercise.  $\square$

### 4.3 Approximation by $C^\infty(\overline{\Omega})$ -Functions

We now ask the question whether any  $u \in W^{k,p}(\Omega)$  can also be approximated by functions  $u_m \in C^\infty(\overline{\Omega})$  instead of  $u_m \in C^\infty(\Omega)$ . The following example shows that this is not true for all open  $\Omega \subset \mathbb{R}^n$ .

**Example 4.8.** Let  $\Omega = \{(x, y) \in \mathbb{R}^2 : 0 < |x| < 1, 0 < y < 1\}$  and  $p \in [1, \infty)$ . Then  $u : \Omega \rightarrow \mathbb{R}$  defined by

$$u(x, y) := \begin{cases} 1 & \text{if } x > 0, \\ 0 & \text{if } x < 0 \end{cases}$$

belongs to  $W^{1,p}(\Omega)$ , but for  $\varepsilon > 0$  sufficiently small there is no  $\varphi \in C^1(\overline{\Omega})$  such that  $\|\varphi - u\|_{W^{1,p}(\Omega)} < \varepsilon$ . (Exercise)

The problem with  $\Omega$  in the example is that it lies on both sides of the segment  $\Gamma = \{(0, y) : y \in [0, 1]\}$  with  $\gamma \subset \partial\Omega$ . The following condition excludes this situation. Moreover, we assume from now on that  $\Omega$  is a domain, i.e. open and connected.

**Definition 4.9.** Let  $\Omega \subset \mathbb{R}^n$  be a domain. We say that  $\Omega$  satisfies the *segment condition* if for any  $x \in \partial\Omega$  there exists a neighborhood  $U_x \subset \mathbb{R}^n$  of  $x$  and  $0 \neq y_x \in \mathbb{R}^n$  such that  $z + ty_x \in \Omega$  for any  $z \in \overline{\Omega} \cap U_x$  and any  $t \in (0, 1)$ .

Another condition on  $\partial\Omega$  is that it is locally the graph of a  $C^m$  function.

**Definition 4.10.** Let  $\Omega \subset \mathbb{R}^n$  be a bounded domain and  $m \in \mathbb{N}$ . We say that  $\Omega$  is of class  $C^m$  or simply  $\partial\Omega \in C^m$  if for any  $x^0 \in \partial\Omega$  there exist  $r = r(x^0) > 0$  and  $\gamma = \gamma_{x^0} \in C^m(\mathbb{R}^{n-1})$  such that, upon relabelling and reorienting the coordinate axes if necessary, we have

$$\begin{aligned}\Omega \cap B_r(x^0) &= \{x \in B_r(x^0) : x_n > \gamma(x_1, \dots, x_{n-1})\}, \\ \partial\Omega \cap B_r(x^0) &= \{x \in B_r(x^0) : x_n = \gamma(x_1, \dots, x_{n-1})\}.\end{aligned}$$

Furthermore, we say  $\partial\Omega \in C^\infty$  if  $\gamma \in C^\infty$  and we say  $\partial\Omega$  is *analytic* if  $\gamma$  is analytic.

*Remark 4.11.* Let  $\Omega$  be a bounded domain with  $\partial\Omega \in C^1$ . Then for any  $x^0 \in \partial\Omega$  there is a unique outward unit vector  $\nu(x^0)$ , i.e.  $|\nu| = 1$ ,  $\nu(x^0) \perp y$  for all  $y \in T(x^0)$ , where  $T(x^0)$  is the tangential space on  $\partial\Omega$  in  $x^0$  and  $x^0 + t\nu(x^0) \notin \overline{\Omega}$  for all  $t \in (0, \varepsilon_0)$  for  $\varepsilon_0 > 0$  small.

Indeed, as

$$\partial\Omega \cap B_r(x^0) = \left\{ x \in B_r(x^0) : x = \begin{pmatrix} x_1 \\ \vdots \\ x_{n-1} \\ \gamma(x_1, \dots, x_{n-1}) \end{pmatrix} \right\}$$

we have that

$$T(x) = \text{span} \left\{ \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \\ \gamma_{x_1}(x_1, \dots, x_{n-1}) \end{pmatrix}, \dots, \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1 \\ \gamma_{x_{n-1}}(x_1, \dots, x_{n-1}) \end{pmatrix} \right\}$$

is  $(n-1)$ -dimensional so that  $T(x)^\perp$  is one-dimensional. Hence,  $\nu(x)$  is uniquely defined and  $\nu : \partial\Omega \rightarrow \mathbb{R}^n$  is continuous as  $\gamma \in C^1(\mathbb{R}^{n-1})$  and

$$\nu(x) = \frac{1}{\sqrt{1 + |\nabla\gamma|^2}} (\gamma_{x_1}, \dots, \gamma_{x_{n-1}}, -1)^T.$$

In particular,  $\Omega$  satisfies the segment condition with  $y_x = -\alpha\nu(x)$  and  $U_x = B_\rho(x)$  with some  $\rho \in (0, r)$  and  $\alpha > 0$  small enough (as  $\nu$  is continuous).  $\square$

Next we prove that in fact  $C^\infty(\overline{\Omega})$  is dense in  $W^{k,p}(\Omega)$  if  $\Omega$  satisfies the segment condition. As a final preparation we need the continuity of the translation in  $L^p(\mathbb{R}^n)$ .

**Proposition 4.12.** Let  $p \in [1, \infty)$  and  $u \in L^p(\mathbb{R}^n)$ . Then the translation is continuous in  $L^p(\mathbb{R}^n)$  in the sense that we have (with  $h \in \mathbb{R}^n$ )

$$\lim_{|h| \rightarrow 0} \|u(\cdot + h) - u(\cdot)\|_{L^p(\mathbb{R}^n)} = 0.$$

*Proof.* Given  $\delta > 0$ , by 2.3 there is  $\varphi \in C_0^\infty(\mathbb{R}^n)$  such that

$$\|u - \varphi\|_{L^p(\mathbb{R}^n)} < \frac{\delta}{3}.$$

But then also

$$\|u(\cdot + h) - \varphi(\cdot + h)\|_{L^p(\mathbb{R}^n)} = \|u - \varphi\|_{L^p(\mathbb{R}^n)} < \frac{\delta}{3}.$$

Since  $\varphi$  has compact support, it is uniformly continuous on  $\mathbb{R}^n$ . Hence, there is  $M > 0$  such that

$$|\varphi(x + h) - \varphi(x)| < \frac{\delta}{3|\text{supp}(\varphi)|^{\frac{1}{p}}} \quad \text{for all } x \in \mathbb{R}^n, h \in B_M(0).$$

Hence, for  $h \in \mathbb{R}^n$  with  $|h| < M$  we have

$$\begin{aligned} \|u(\cdot + h) - u(\cdot)\|_{L^p(\mathbb{R}^n)} &\leq \|u(\cdot + h) - \varphi(\cdot + h)\|_{L^p(\mathbb{R}^n)} + \|\varphi(\cdot + h) - \varphi(\cdot)\|_{L^p(\mathbb{R}^n)} + \|\varphi - u\|_{L^p(\mathbb{R}^n)} \\ &\leq \frac{2}{3}\delta + \|\varphi(\cdot + h) - \varphi(\cdot)\|_{L^\infty(\mathbb{R}^n)} |\text{supp}(\varphi)|^{\frac{1}{p}} \\ &< \delta \end{aligned}$$

and the claim follows.  $\square$

**Theorem 4.13.** *Let  $\Omega \subset \mathbb{R}^n$  be a domain satisfying the segment condition,  $k \in \mathbb{N}$ , and  $p \in [1, \infty)$ . Then the set  $\{\varphi|_\Omega : \varphi \in C_0^\infty(\mathbb{R}^n)\}$  is dense in  $W^{k,p}(\Omega)$ . In particular, if in addition  $\Omega \neq \mathbb{R}^n$ , then for any  $u \in W^{k,p}(\Omega)$  there is  $(u_m)_{m \in \mathbb{N}} \subset C^\infty(\overline{\Omega})$  such that  $u_m \rightarrow u$  in  $W^{k,p}(\Omega)$ .*

*Proof.* We fix  $u \in W^{k,p}(\Omega)$  and  $\delta > 0$ .

- i) In a first step, we show that in case  $\Omega$  is unbounded there exists  $v \in W^{k,p}(\Omega)$  with  $\text{supp}(v)$  bounded and  $\|u - v\|_{W^{k,p}(\Omega)} < \delta$ . By Lemma 4.2, there exists  $\tau \in C_0^\infty(B_2(0))$  such that  $0 \leq \tau \leq 1$ ,  $\tau \equiv 1$  in  $\overline{B_1(0)}$  and there is some  $M = M(k) > 0$  such that  $|D^\alpha \tau(x)| \leq M$  for all  $x \in \mathbb{R}^n$  and all  $|\alpha| \leq k$  (choose  $K = \overline{B_1(0)}$ ,  $\Omega = B_2(0)$ ,  $\delta = 1$  in Lemma 4.2). For  $\varepsilon \in (0, 1)$ , we define  $\tau_\varepsilon := \tau(\varepsilon x)$ ,  $x \in \mathbb{R}^n$ . Then  $\tau_\varepsilon \equiv 1$  in  $\overline{B_{\frac{1}{\varepsilon}}(0)}$ ,  $\tau_\varepsilon \in C_0^\infty(B_{\frac{2}{\varepsilon}}(0))$ , and

$$(4.4) \quad |D^\alpha \tau_\varepsilon(x)| \leq M\varepsilon^{|\alpha|} \leq M \quad \text{for all } |\alpha| \leq k.$$

Hence,  $v_\varepsilon := \tau_\varepsilon u$  has bounded support and belongs to  $W^{k,p}(\Omega)$  by Proposition 3.8 d). It further satisfies for  $|\alpha| \leq k$

$$|D^\alpha v_\varepsilon(x)| = \left| \sum_{\beta \leq \alpha} \binom{\alpha}{\beta} D^\beta \tau_\varepsilon(x) D^{\alpha-\beta} u(x) \right| \leq M \sum_{\beta \leq \alpha} \binom{\alpha}{\beta} |D^{\alpha-\beta} u(x)| \quad \text{for all } x \in \Omega$$

so that for all  $\tilde{\Omega} \subset \Omega$  open we have

$$\|v_\varepsilon\|_{W^{k,p}(\tilde{\Omega})} \leq \sum_{|\alpha| \leq k} \|D^\alpha v_\varepsilon\|_{L^p(\tilde{\Omega})} \leq M \left( \sum_{|\alpha| \leq k} \sum_{\beta \leq \alpha} \binom{\alpha}{\beta} \right) \|u\|_{W^{k,p}(\tilde{\Omega})} \leq c(k)M \|u\|_{W^{k,p}(\tilde{\Omega})}$$

with some constant  $c(k) > 0$ . Hence,

$$\begin{aligned} \|u - v_\varepsilon\|_{W^{k,p}(\Omega)} &= \|u - v_\varepsilon\|_{W^{k,p}(\Omega \setminus \overline{B_{\frac{1}{\varepsilon}}(0)})} \leq \|u\|_{W^{k,p}(\Omega \setminus \overline{B_{\frac{1}{\varepsilon}}(0)})} + \|v_\varepsilon\|_{W^{k,p}(\Omega \setminus \overline{B_{\frac{1}{\varepsilon}}(0)})} \\ &\leq (1 + c(k)M) \|u\|_{W^{k,p}(\Omega \setminus \overline{B_{\frac{1}{\varepsilon}}(0)})} \\ &\rightarrow 0 \quad \text{as } \varepsilon \rightarrow 0 \end{aligned}$$

in view of  $p < \infty$ . Hence,  $\|u - v_\varepsilon\|_{W^{k,p}(\Omega)} < \delta$  for  $\varepsilon > 0$  small enough and  $v = v_\varepsilon$  has bounded support.

- ii) In view of i) we may assume w.l.o.g. that  $K := \text{supp}(u)$  is bounded and hence compact (if necessary, we replace  $u$  by  $v$ ).

For  $x \in \partial\Omega$ , let  $U_x \subset \mathbb{R}^n$  be the open neighborhood of  $x$  and  $0 \neq y_x \in \mathbb{R}^n$  like in Definition 4.9. Then

$$F := K \setminus \left( \bigcup_{x \in \partial\Omega} U_x \right)$$

is compact with  $F \subset \Omega$ . Hence, there is  $U_0$  open such that  $F \Subset U_0 \Subset \Omega$ . As  $K$  is compact, there exist finitely many of the sets  $U_x$  which we call  $U_1, \dots, U_N$  such that  $K \subset \bigcup_{i=0}^N U_i$ . Moreover, we choose  $V_i \Subset U_i$  open sets,  $i = 0, \dots, N$ , such that  $K \subset \bigcup_{i=0}^N V_i$  and  $V_i$  is still a neighborhood of  $x^i$  belonging to  $U_i = U_{x^i}$ . By Lemma 4.3 there is a partition of unity  $\psi_0, \dots, \psi_N$  such that  $\psi_i \in C_0^\infty(V_i)$ ,  $0 \leq \psi_i \leq 1$  for  $i = 0, \dots, N$ , and  $\sum_{i=0}^N \psi_i(x) = 1$  for all  $x \in K$ .

Our aim is to find  $\varphi_i \in C_0^\infty(\mathbb{R}^n)$  such that with  $u_i := \psi_i u$  we have

$$(4.5) \quad \|u_i - \varphi_i\|_{W^{k,p}(\Omega)} < \frac{\delta}{N+1} \quad \text{for all } i \in \{0, \dots, N\}.$$

As  $\text{supp}(u_0) \Subset V_0 \Subset \Omega$ , by Theorems 4.1 and 2.1 b) there exists  $\varphi_0 \in C_0^\infty(\mathbb{R}^n)$  such that (4.5) holds for  $i = 0$ . Next, we fix  $i \in \{1, \dots, N\}$  and extend  $u$  by 0 outside  $\Omega$ . Let  $x^i \in \partial\Omega$  be the point belonging to  $U_i$  ( $U_i$  is a neighborhood of  $x^i$ ) and

$$\Gamma := \overline{V_i} \cap \partial\Omega.$$

As  $\psi_i = 0$  on  $\partial\Omega \setminus \Gamma$ ,  $u_i = 0$  on  $\mathbb{R}^n \setminus \overline{\Omega}$ , and  $u_i \in W^{k,p}(\Omega)$  by Proposition 3.8, we get  $u_i \in W^{k,p}(\mathbb{R}^n \setminus \Gamma)$ . Let  $y := y_{x^i}$  from the segment condition and

$$\Gamma_t := \{x - ty : x \in \Gamma\},$$

where

$$0 < t < \min\left\{1, \frac{1}{|y|} \text{dist}(\partial V_i, \partial U_i)\right\}.$$

By the choice of  $t$ , we have  $\Gamma_t \subset U_i$  and  $\Gamma_t \cap \overline{\Omega} = \emptyset$ . The latter follows from the segment condition: For  $z = x - sy$  with  $x \in \Gamma$  and  $s \in (0, 1)$  we have  $z + sy = x \in \Gamma \subset \partial\Omega$ . Hence,  $z \notin \overline{\Omega}$  so that  $\Gamma_t \cap \overline{\Omega} = \emptyset$ . Define

$$w_t(x) := u_i(x + ty) \quad \text{for all } x \in \mathbb{R}^n.$$

As  $u_i \in W^{k,p}(\mathbb{R}^n \setminus \Gamma)$ , we have  $w_t \in W^{k,p}(\mathbb{R}^n \setminus \Gamma_t)$ . Hence, Proposition 4.12 yields that  $D^\alpha w_t \rightarrow D^\alpha u_i$  in  $L^p(\Omega)$  as  $t \downarrow 0$  for all  $|\alpha| \leq k$  (since  $\overline{\Omega} \subset \mathbb{R}^n \setminus \Gamma_t$ ) and we can choose  $t$  small enough such that  $\|w_t - u_i\|_{W^{k,p}(\Omega)} \leq \frac{\delta}{2(N+1)}$ .

Moreover, since  $u \in L^p(\Omega)$  and  $u = 0$  on  $\mathbb{R}^n \setminus \Omega$ , we have  $u \in L^p(\mathbb{R}^n)$ ,  $u_i = \psi_i u \in L^p(\mathbb{R}^n)$ , and  $w_t \in L^p(\mathbb{R}^n)$ . Since  $\text{supp}(u_i) \subset \overline{\Omega} \cap V_i$ ,  $w_t$  has compact support in  $\mathbb{R}^n$ . Hence, by Theorem 2.1  $\varphi_i := \eta_\varepsilon * w_t$  belongs to  $C_0^\infty(\mathbb{R}^n)$  for  $\varepsilon > 0$ . As  $\text{dist}(\Gamma_t, \overline{\Omega}) > 0$ , we may



choose  $\varepsilon > 0$  small enough such that  $\|\varphi_i - w_t\|_{W^{k,p}(\Omega)} < \frac{\delta}{2(N+1)}$  (as  $\Omega \cap \text{supp}(w_t) \Subset \mathbb{R}^n \setminus \Gamma_t$  and  $w_t \in W^{k,p}(\mathbb{R}^n \setminus \Gamma_t)$  we may apply Theorem 4.1). Altogether,  $\varphi_i \in C_0^\infty(\mathbb{R}^n)$  satisfies  $\|u_i - \varphi_i\| \leq \frac{\delta}{N+1}$  and (4.5) holds for all  $i \in \{0, \dots, N\}$ . As  $u = \sum_{i=1}^N u_i$ , the function

$$\varphi := \sum_{i=0}^N \varphi_i \in C_0^\infty(\mathbb{R}^n)$$

satisfies  $\|u - \varphi\|_{W^{k,p}(\Omega)} \leq \delta$ .

iii) Combining i) and ii), the claim is proved.  $\square$

As a Corollary, we see that  $W_0^{k,p}(\mathbb{R}^n)$  and  $W^{k,p}(\mathbb{R}^n)$  coincide.

**Corollary 4.14.** *For  $k \in \mathbb{N}$  and  $p \in [1, \infty)$ , we have  $W_0^{k,p}(\mathbb{R}^n) = W^{k,p}(\mathbb{R}^n)$ .*

*Proof.* Given  $u \in W^{k,p}(\mathbb{R}^n)$  by part i) of the proof of Theorem 4.13, there exists  $v \in W^{k,p}(\mathbb{R}^n)$  with  $K := \text{supp}(V)$  compact and

$$\|u - v\|_{W^{k,p}(\mathbb{R}^n)} \leq \frac{\delta}{2}.$$

But then there is  $V_0$  open such that  $K \Subset V_0 \Subset \mathbb{R}^n$  and by Theorems 4.1 and 2.1 b) there is  $\varepsilon > 0$  small enough such that  $v_\varepsilon = \eta_\varepsilon * v \in C_0^\infty(V_0)$  and

$$\|v - v_\varepsilon\|_{W^{k,p}(\mathbb{R}^n)} = \|v - v_\varepsilon\|_{W^{k,p}(V_0)} < \frac{\delta}{2}.$$

Hence,  $\|u - v_\varepsilon\|_{W^{k,p}(\mathbb{R}^n)} < \delta$  and  $v_\varepsilon \in C_0^\infty(\mathbb{R}^n)$ .  $\square$

## Chapter 5

# Extension and Traces

Here, we will study how we can extend functions in  $W^{k,p}(\Omega)$  to  $W^{k,p}(\mathbb{R}^n)$ . Moreover, we will see how we can define boundary values on  $\partial\Omega$  of functions in  $W^{k,p}(\Omega)$ .

### 5.1 Flattening the Boundary

We will frequently use that if  $\Omega$  is a bounded domain with  $\partial\Omega \in C^m$ , we can transform  $\Omega \cap B_r(x^0)$  for  $x^0 \in \partial\Omega$  to a domain having a flat boundary, where the transformation is a  $C^m$ -diffeomorphism. This will be done in details here.

*Notation 5.1.* We define

$$\mathbb{R}_+^n := \{x \in \mathbb{R}^n : x_n > 0\}, \quad \mathbb{R}_-^n := \{x \in \mathbb{R}^n : x_n < 0\},$$

and for  $U \subset \mathbb{R}^n$

$$U^+ := U \cap \mathbb{R}_+^n, \quad U^- := U \cap \mathbb{R}_-^n, \quad U^0 := \{x \in U : x_n = 0\}.$$

Moreover, we write  $x = (x', x_n)$  for  $x \in \mathbb{R}^n$  with  $x = (x_1, \dots, x_n)$  and  $x' = (x_1, \dots, x_{n-1}) \in \mathbb{R}^{n-1}$ .

**Definition 5.2.** Let  $\Omega$  and  $U$  be domains in  $\mathbb{R}^n$ . A map  $g: \Omega \rightarrow U$  is called  $C^m$ -diffeomorphism if and only if  $g$  is bijective,  $g \in C^m(\overline{\Omega}, \mathbb{R}^n)$ ,  $g^{-1} \in C^m(\overline{U}, \mathbb{R}^n)$  and  $\det(Dg) \neq 0$  in  $\overline{\Omega}$ .

If  $\partial\Omega \in C^m$ , then we can locally transform  $\Omega$  to a domain with flat boundary.

**Lemma 5.3.** Let  $m \in \mathbb{N}$  and  $\gamma \in C^m(\mathbb{R}^{n-1})$ . Then  $\Phi: \mathbb{R}^n \rightarrow \mathbb{R}^n$  and  $\Psi: \mathbb{R}^n \rightarrow \mathbb{R}^n$  defined by

$$\begin{aligned} \Phi(x) &= (x_1, \dots, x_{n-1}, x_n - \gamma(x')), \\ \Psi(y) &= (y_1, \dots, y_{n-1}, y_n + \gamma(y')), \quad x, y \in \mathbb{R}^n, \end{aligned}$$

satisfy  $\Phi, \Psi \in C^m(\mathbb{R}^n, \mathbb{R}^n)$ ,  $\det(D\Phi) = \det(D\Psi) = 1$  on  $\mathbb{R}^n$ , and  $\Phi^{-1} = \Psi$ . In particular, for any bounded domain  $\Omega$ ,  $\Phi|_\Omega: \Omega \rightarrow \Phi(\Omega)$  is a  $C^m$ -diffeomorphism. If  $\partial\Omega \in C^m$  and

$$\begin{aligned} \Omega \cap B_r(x^0) &= \{x \in B_r(x^0) : x_n > \gamma(x')\}, \\ \partial\Omega \cap B_r(x^0) &= \{x \in B_r(x^0) : x_n = \gamma(x')\} \end{aligned}$$

for some  $x^0 \in \partial\Omega$  (see Definition 4.10), then  $\Phi: B_r(x^0) \rightarrow U := \Phi(B_r(x^0))$  is a  $C^m$ -diffeomorphism with  $\Phi(\Omega \cap B_r(x^0)) = U^+$  and  $\Phi(\partial\Omega \cap B_r(x^0)) = U^0$ .

*Proof.* It is straightforward to see that  $\Phi$  and  $\Psi$  are  $C^m$ -functions with  $\Psi = \Phi^{-1}$  and  $\det(D\Phi) = \det(D\Psi) = 1$ . The further claims are immediate consequences of Definition 5.2.  $\square$

$\Phi$  now provides a transformation which *flattens* the boundary. A  $C^m$ -diffeomorphism also provides a transformation between the corresponding Sobolev spaces.

**Proposition 5.4.** *Let  $g: U \rightarrow \Omega$  be a  $C^m$ -diffeomorphism with  $m \in \mathbb{N}$ ,  $p \in [1, \infty)$ , and  $\Omega, U \subset \mathbb{R}^n$  bounded domains. Then the map  $T_g: W^{m,p}(\Omega) \rightarrow W^{m,p}(U)$ , defined by*

$$(T_g(u))(y) := u(g(y)), \quad y \in U, u \in W^{m,p}(\Omega),$$

*is bijective and there exist  $C_1, C_2 > 0$  such that*

$$\|T_g(u)\|_{W^{m,p}(U)} \leq C_1 \|u\|_{W^{m,p}(\Omega)} \quad \text{and} \quad \|(T_g)^{-1}(v)\|_{W^{m,p}(\Omega)} \leq C_2 \|v\|_{W^{m,p}(U)}$$

*for all  $u \in W^{m,p}(\Omega)$ ,  $v \in W^{m,p}(U)$ , where  $(T_g)^{-1} = T_{g^{-1}}$ .*

*Proof.* i) If  $T_g$  is well-defined and satisfies the claimed estimate, it is immediate that  $(T_g)^{-1} = T_{g^{-1}}$  and hence the estimate for  $(T_g)^{-1}$  follows by replacing  $g$  by  $g^{-1}$ . Moreover, we only consider the case  $m = 1$  as the general case then follows by induction.

ii) Let  $m = 1$  and  $T := T_g$ . Assume first that  $u \in C^\infty(\Omega) \cap W^{1,p}(\Omega)$ . Then the chain rule and the transformation rule imply with  $M := \|\det(Dg^{-1})\|_{C^0(\bar{\Omega})}$

$$(5.1) \quad \int_U |T(u)(y)|^p dy = \int_\Omega |u(x)|^p |\det(Dg^{-1})(x)| dx \leq M \int_\Omega |u(x)|^p dx,$$

$$\partial_{y_i}(T(u))(y) = \sum_{j=1}^n u_{x_j}(x) \cdot (g_j)_{y_i}(y) = \sum_{j=1}^n T(u_{x_j})(y) \cdot (g_j)_{y_i}(y), \quad y \in U,$$

where  $x = g(y)$  ( $x \in \Omega, y \in U$ ), and

$$\begin{aligned} \left( \int_U |(\partial_{y_i}(T(u)))(y)|^p dy \right)^{\frac{1}{p}} &\leq \|g\|_{C^1(\bar{U})} \sum_{j=1}^n \left( \int_U |T(u_{x_j})(y)|^p dy \right)^{\frac{1}{p}} \\ &\stackrel{(5.1)}{\leq} \|g\|_{C^1(\bar{U})} M^{\frac{1}{p}} \sum_{j=1}^n \|u_{x_j}\|_{L^p(\Omega)}. \end{aligned}$$

Hence,  $\|T(u)\|_{W^{1,p}(U)} \leq M^{\frac{1}{p}}(1 + n\|g\|_{C^1(\bar{U})}) \|u\|_{W^{1,p}}$  by combining the previous estimate with (5.1) and Minkowski's inequality.

iii) By ii) we have

$$\|T(u)\|_{W^{1,p}(U)} \leq C_1 \|u\|_{W^{1,p}(\Omega)} \quad \text{for all } u \in C^\infty(\Omega) \cap W^{1,p}(\Omega).$$

For  $u \in W^{1,p}(\Omega)$  there exists  $(u_k)_{k \in \mathbb{N}} \subset C^\infty(\Omega) \cap W^{1,p}(\Omega)$  such that  $u_k \rightarrow u$  in  $W^{1,p}(\Omega)$  and a.e. in  $\Omega$ . As  $T$  is linear, we have

$$\|T(u_k) - T(u_j)\|_{W^{1,p}(U)} \leq C_1 \|u_k - u_j\|_{W^{1,p}(\Omega)}, \quad \text{for all } k, j \in \mathbb{N}.$$

Hence,  $(T(u_k))_{k \in \mathbb{N}}$  is a Cauchy sequence in  $W^{1,p}(U)$  and  $T(u_k) \rightarrow v$  in  $W^{1,p}(U)$ . As obviously  $T(u_k) \rightarrow T(u)$  in  $L^p(U)$  by (5.1) and the dominated convergence theorem, we have  $v = T(u) \in W^{1,p}(U)$  and

$$\|T(u)\|_{W^{1,p}(U)} = \lim_{k \rightarrow \infty} \|T(u_k)\|_{W^{1,p}(U)} \stackrel{\text{ii)}}{\leq} C_1 \lim_{k \rightarrow \infty} \|u_k\|_{W^{1,p}(\Omega)} = C_1 \|u\|_{W^{1,p}(\Omega)},$$

where  $C_1$  can be chosen independent of  $p$  as  $M^{\frac{1}{p}} \leq 1 + M$ .  $\square$

## 5.2 Extension Theorem

We next extend functions  $u \in W^{k,p}(\Omega)$  to become a function in  $W^{k,p}(\mathbb{R}^n)$ . This cannot be done in general by extending  $u$  by 0 to  $\mathbb{R}^n \setminus \Omega$  as this may create bad discontinuities in some  $D^\alpha u$  on  $\partial\Omega$ . We need now again boundary regularity of  $\partial\Omega$ .

**Theorem 5.5.** *Let  $m \in \mathbb{N}$ ,  $p \in [1, \infty)$ ,  $\Omega \subset \mathbb{R}^n$  be a bounded domain with  $\partial\Omega \in \mathbb{C}^m$ , and  $V \subset \mathbb{R}^n$  be a domain with  $\Omega \Subset V$ . Then for any  $k \in \{1, \dots, m\}$  there exists a linear Operator*

$$E: W^{k,p}(\Omega) \rightarrow W^{k,p}(\mathbb{R}^n)$$

*such that*

- a)  $E(u) = u$  a.e. in  $\Omega$ ,
- b)  $\text{supp}(E(u)) \Subset V$ , i.e.  $E(u) \in W_0^{k,p}(V)$ ,
- c)  $\|E(u)\|_{W^{k,p}(\mathbb{R}^n)} \leq C \|u\|_{W^{k,p}(\Omega)}$  for all  $u \in W^{k,p}(\Omega)$ ,

*where  $C > 0$  depends on  $m, p, V$ , and  $\Omega$  but not on  $k$  and  $u$ . Moreover,  $E$  does not depend on  $k \in \{1, \dots, m\}$  and on  $p \in [1, \infty)$  in the sense that if  $u \in W^{k,p}(\Omega)$  for several  $p, k$  then  $E(u)$  is uniquely determined in all these spaces.*

*Proof.* We will use the notation from 5.1, Lemma 5.3, and Definition 4.10.

- i) We first assume that for some  $x^0 \in \partial\Omega$ ,  $B := B_r(x^0)$  satisfies  $\Omega \cap B = B^+$  and  $\partial\Omega \cap B = B^0$ . We further assume that  $u \in C^m(B^+ \cup B^0)$  with  $\text{supp}(u) \subset \tilde{B}^+ := \overline{(B_s(x^0))^+}$  for some  $s \in (0, r)$ . As hence  $u = 0$  in a neighborhood of  $\partial B \cap \overline{\mathbb{R}_+^n}$ , we can extend  $u$  by 0 in  $\overline{\mathbb{R}_+^n} \setminus B^+$  and have  $u \in C^m(\overline{\mathbb{R}_+^n})$  with  $\text{supp}(u) \subset \tilde{B}^+$ . Then we extend  $u$  from  $\overline{\mathbb{R}_+^n}$  to  $\mathbb{R}^n$  by a *higher-order reflection*. The  $(m+1) \times (m+1)$  system of linear equations

$$(5.2) \quad \sum_{j=1}^{m+1} (-j)^i \lambda_j = 1, \quad i = 0, \dots, m,$$

has a unique solution  $(\lambda_1, \dots, \lambda_{m+1})$  since the corresponding matrix is of Vandermonde type. We define the extension

$$\tilde{E}(u)(x) := \begin{cases} u(x) & \text{if } x = (x', x_n) \text{ with } x_n \geq 0, \\ \sum_{j=1}^{m+1} \lambda_j u(x', -jx_n) & \text{if } x = (x', x_n) \text{ with } x_n < 0, \end{cases}$$

and for any  $\alpha \in \mathbb{N}_0^n$  with  $1 \leq |\alpha| \leq m$

$$\tilde{E}_\alpha(u)(x) := \begin{cases} u(x) & \text{if } x_n \geq 0, \\ \sum_{j=1}^{m+1} (-j)^{\alpha_n} \lambda_j u(x', -jx_n) & \text{if } x_n < 0. \end{cases}$$

Then for all  $|\alpha| \leq m$  we have  $D^\alpha(\tilde{E}(u)) = \tilde{E}_\alpha(D^\alpha u)$  and hence  $\tilde{E}(u) \in C^n(\mathbb{R}^n)$ : This is immediate in  $\mathbb{R}_+^n$  and  $\mathbb{R}_-^n$ , while for  $x \in \partial\mathbb{R}_+^n$ , namely  $x_n = 0$ , we have

$$\begin{aligned} \lim_{t \uparrow 0} D^\alpha(\tilde{E}(u))(x', t) &= \lim_{t \uparrow 0} \tilde{E}_\alpha(D^\alpha u)(x', t) = \lim_{t \uparrow 0} \sum_{j=1}^{m+1} (-j)^{\alpha_n} \lambda_j D^\alpha u(x', -jt) \\ &= \left( \sum_{j=1}^{m+1} (-j)^{\alpha_n} \lambda_j \right) D^\alpha u(x', 0) \stackrel{(5.2)}{=} D^\alpha u(x', 0) \\ &= \lim_{t \downarrow 0} D^\alpha u(x', t) = \lim_{t \downarrow 0} D^\alpha(\tilde{E}(u))(x', t) \end{aligned}$$

since  $u \in C^m(\overline{\mathbb{R}_+^n})$  by assumption. Moreover,

$$\begin{aligned} \|D^\alpha(\tilde{E}(u))\|_{L^p(\mathbb{R}^n)} &\leq \left( 1 + \sum_{j=1}^{m+1} j^{\alpha_n} |\lambda_j| j^{\frac{1}{p}} \right) \|D^\alpha u\|_{L^p(\mathbb{R}_+^n)} \\ &\stackrel{p \geq 1}{\leq} \left( 1 + \sum_{j=1}^{m+1} j^{\alpha_n+1} |\lambda_j| \right) \|D^\alpha u\|_{L^p(\mathbb{R}_+^n)}, \end{aligned}$$

where we have used the transformation rule with  $z = (x', -jx_n)$  and  $\text{supp}(u) \subset \tilde{B}_+ \subset \overline{B}^+$ . Hence,  $\tilde{E}(u) \in C^m(\mathbb{R}^n)$  with

$$(5.3) \quad \|\tilde{E}(u)\|_{W^{k,p}(\mathbb{R}^n)} \leq C_1 \|u\|_{W^{k,p}(B^+)}$$

with  $C_1$  depending on  $m$  and  $n$ .

- ii) As  $\partial\Omega \in C^m$  and  $\partial\Omega$  is compact, there exists  $x^i \in \partial\Omega$  and balls  $U_i := B_r(x^i)$ ,  $i = 1, \dots, N$ , such that after relabelling and reorienting the coordinate axes (described by a  $C^\infty$ -diffeomorphism  $\mathcal{T}_i: \mathbb{R}^n \rightarrow \mathbb{R}^n$ ), we have

$$\begin{aligned} \Omega \cap U_i &= \{x \in U_i: x_n > \gamma_i(x')\} \\ \partial\Omega \cap U_i &= \{x \in U_i: x_n = \gamma_i(x')\} \end{aligned}$$

with  $\gamma_i \in C^m(\mathbb{R}^{n-1})$ . Choose  $U_0 \Subset \Omega$  such that  $\overline{\Omega} \subset \bigcup_{i=0}^N U_i$ . By Lemma 4.3 there exists a partition of unity  $\varphi_i \in C_0^\infty(\mathcal{T}_i^{-1}(U_i))$  with  $0 \leq \varphi_i \leq 1$  and  $\sum_{i=1}^N \varphi_i(x) = 1$  for all  $x \in \overline{\Omega}$ . Define further  $\Phi_i, \Psi_i$  by Lemma 5.3 according to  $\gamma = \gamma_i$ ,  $i = 1, \dots, N$ , and set  $W_i := \Phi_i(U_i)$ .

We fix  $i \in \{1, \dots, N\}$  and  $u \in C^m(\overline{\Omega})$ . Then  $\varphi_i u$  and hence also  $T_{\mathcal{T}_i^{-1}}(\varphi_i u)$  belong to  $C^m(\overline{U_i} \cap \overline{\Omega})$  with compact support  $K_i \Subset U_i$ ,  $K_i \subset \mathcal{T}_i(\overline{\Omega})$ . Then

$$v_i := T_{\Psi_i}(T_{\mathcal{T}_i^{-1}}(\varphi_i u)) \in C^m(\overline{W_i^+})$$

with support in  $\Phi(K_i) \Subset W_i$  and  $\Phi_i(K_i) \subset W_i^+ \cup W_i^0$ . Hence, we may apply  $\tilde{E}$  to  $v_i$  (by choosing  $\tilde{B}^+$  and  $B$  appropriately such that  $\Phi_i(K_i) \subset \tilde{B}^+ \Subset W_i \Subset B$ ) and obtain

$$\tilde{E}(v_i) \in C^m(\mathbb{R}^n) \cap W^{k,p}(\mathbb{R}^n).$$

Transforming back, we finally obtain

$$u_i := T_{\mathcal{T}_i}(T_{\Phi_i}(\tilde{E}(v_i))) \in W^{k,p}(\mathbb{R}^n).$$

As  $\tilde{E}(v_i)$  has compact support in some ball  $B_i \subset \mathbb{R}^n$ , we may apply Proposition 5.4 with

$$\Phi_i := \Phi_i^{-1}(B_i) \rightarrow B_i \quad \text{and} \quad \mathcal{T}_i: \mathcal{T}_i^{-1}(\Phi_i^{-1}(B_i)) \rightarrow \Phi_i^{-1}(B_i)$$

and obtain  $u_i = \varphi_i u$  in  $\Omega$  and

$$\begin{aligned} \|u_i\|_{W^{k,p}(\mathbb{R}^n)} &\leq C_2 \|\tilde{E}(v_i)\|_{W^{k,p}(B_i)} \stackrel{\text{i)}}{\leq} C_3 \|v_i\|_{W^{k,p}(W_i^+)} \\ &\stackrel{\text{Prop. 5.4}}{\leq} C_4 \|\varphi_i u\|_{W^{k,p}(\Omega \cap U_i)} \stackrel{\text{Prop. 3.8 Lem. 4.2}}{\leq} C_5 \|u\|_{W^{k,p}(\Omega \cap U_i)}. \end{aligned}$$

Defining further  $u_0 := \varphi_0 u \in C^m(U_0)$  with compact support in  $U_0$ , we have

$$\sum_{i=0}^n u_i \in W^{k,p}(\mathbb{R}^n) \quad \text{with} \quad \left\| \sum_{i=0}^N u_i \right\|_{W^{k,p}(\mathbb{R}^n)} \leq C_6 \|u\|_{W^{k,p}(\Omega)}$$

and

$$\sum_{i=0}^N u_i = \sum_{i=0}^N \varphi_i u = u \quad \text{in } \Omega.$$

Finally, let  $\tau \in C_0^\infty(V)$  be the cutoff-function w.r.t  $\bar{\Omega}$  and  $V$ . Then

$$E(u) := \tau \cdot \sum_{i=0}^N u_i \in W^{k,p}(\mathbb{R}^n) \quad \text{with} \quad \text{supp}(E(u)) \Subset V$$

and

$$(5.4) \quad \|E(u)\|_{W^{k,p}(\mathbb{R}^n)} \leq C_7 \|u\|_{W^{k,p}(\Omega)} \quad \text{for all } u \in C^m(\bar{\Omega}),$$

where  $C_7 > 0$  does not depend on  $k$  or  $u$  but on  $m, p, \Omega$  and  $V$ . Moreover,  $E(u) = u$  in  $\Omega$ .

iii) As  $\tilde{E}$  is linear in  $u$  and  $T_g$  is linear in  $u$  (see Proposition 5.4), the map

$$E: C^m(\bar{\Omega}) \rightarrow W^{k,p}(\mathbb{R}^n), \quad u \mapsto E(u)$$

is linear. Let  $u \in W^{k,p}(\Omega)$ . Then by Theorem 4.13 there exists  $(u_j)_{j \in \mathbb{N}} \subset C^m(\bar{\Omega})$  such that  $u_j \rightarrow u$  in  $W^{k,p}(\Omega)$ . Then by (5.4)

$$\|E(u_j) - E(u_i)\|_{W^{k,p}(\mathbb{R}^n)} \leq C_7 \|u_j - u_i\|_{W^{k,p}(\Omega)} \quad \text{for all } i, j \in \mathbb{N}$$

so that  $(E(u_j))_{j \in \mathbb{N}}$  is a Cauchy sequence in  $W^{k,p}(\mathbb{R}^n)$  and has a limit  $v \in W^{k,p}(\mathbb{R}^n)$ . As  $E(u_j) \rightarrow v$  a.e. in  $\mathbb{R}^n$  for a subsequence, we still have  $\text{supp}(v) \Subset V$  and  $u = v$  a.e. in  $\Omega$ . Defining  $E(u) := v$ , we have

$$\|E(u)\|_{W^{k,p}(\mathbb{R}^n)} \leq C_7 \|u\|_{W^{k,p}(\Omega)}$$

by (5.4) like in the end of the proof of Proposition 5.4. Since (5.4) implies that  $E(u) = u$  does not depend on the choice of the approximating sequence  $(u_j)_{j \in \mathbb{N}}$  (as  $E$  is linear), we thereby have defined  $E: W^{k,p}(\Omega) \rightarrow W^{k,p}(\mathbb{R}^n)$  having all claimed properties.  $\square$

### 5.3 Trace Operator

A function  $u \in W^{1,p}(\Omega) \cap C^0(\overline{\Omega})$  clearly has boundary values on  $\partial\Omega$  in the usual sense. But a general function  $u \in W^{1,p}(\Omega)$  is not continuous and only defined a.e. in  $\Omega$ . Since  $\partial\Omega$  has  $n$ -dimensional Lebesgue measure 0, we need a trace operator involving the space  $L^p(\partial\Omega)$  for assigning boundary values to  $u$ .

**Definition 5.6.** Let  $\Omega$  be a bounded domain with  $\partial\Omega \in C^1$  and  $U_i := B_{r_i}(x^i)$ ,  $i = 1, \dots, N$ , such that  $\Omega \cap U_i = \{x \in U_i : x_n > \gamma_i(x')\}$ ,  $\partial\Omega \cap U_i = \{x \in U_i : x_n = \gamma_i(x')\}$  with  $\gamma_i \in C^1(\mathbb{R}^{n-1})$  and  $x^i \in \partial\Omega$  (where we assume that the coordinate axes are relabeled and reoriented appropriately). Defining

$$U'_i := \{x' : x \in \partial\Omega \cap U_i\} \subset \mathbb{R}^{n-1},$$

we have

$$\partial\Omega \cap U_i = \{(x', \gamma_i(x')) : x' \in U'_i\}.$$

Let  $U$  be a neighborhood of  $\partial\Omega$  (in  $\mathbb{R}^n$ ) such that  $U \Subset \bigcup_{i=1}^N U_i$  and  $\varphi_i$ ,  $i = 1, \dots, N$ , a corresponding partition of unity such that  $\varphi_i \in C_0^\infty(U_i)$ ,  $\sum_{i=1}^N \varphi_i(x) = 1$  for all  $x \in U$ ,  $0 \leq \varphi_i \leq 1$ . Then  $v : \partial\Omega \rightarrow \mathbb{R}$  is called *measurable* on  $\partial\Omega$  if

$$v_i : U'_i \rightarrow \mathbb{R}, \quad v_i(x') := (\varphi_i v)(x', \gamma_i(x'))$$

is measurable in  $U'_i \subset \mathbb{R}^{n-1}$ .

Defining

$$\int_{\partial\Omega} v_i \, d\sigma := \int_{\partial\Omega \cap U_i} v_i \, d\sigma := \int_{U'_i} v_i \sqrt{1 + |\nabla \gamma_i|^2} \, dx'$$

and

$$\int_{\partial\Omega} v \, d\sigma := \sum_{i=1}^N \int_{\partial\Omega} v_i \, d\sigma,$$

then  $L^p(\partial\Omega)$  is the space of functions  $v : \partial\Omega \rightarrow \mathbb{R}$  being measurable on  $\partial\Omega$  such that the norm

$$\|v\|_{L^p(\partial\Omega)} := \left( \int_{\partial\Omega} |v|^p \, d\sigma \right)^{\frac{1}{p}}$$

is finite where  $p \in [1, \infty)$ .

Then we have the following theorem:

**Theorem 5.7** (Trace theorem). *Let  $\Omega$  be a bounded domain with  $\partial\Omega \in C^1$  and  $p \in [1, \infty)$ . Then there exists a bounded linear operator  $\text{Tr} : W^{1,p}(\Omega) \rightarrow L^p(\partial\Omega)$  such that*

$$a) \quad \text{Tr}(u) = u|_{\partial\Omega} \text{ if } u \in W^{1,p}(\Omega) \cap C^0(\overline{\Omega}),$$

$$b) \quad \|\text{Tr}(u)\|_{L^p(\partial\Omega)} \leq C \|u\|_{W^{1,p}(\Omega)} \text{ for any } u \in W^{1,p}(\Omega), \text{ where } C > 0 \text{ only depends on } p \text{ and } \Omega.$$

$\text{Tr}(u)$  is called the trace of  $u$  on  $\partial\Omega$ .

*Proof.* i) Assume like in the proof of Theorem 5.5 that there is  $x^0 \in \partial\Omega$  and  $B := B_r(x^0) \subset \mathbb{R}^n$  such that  $\Omega \cap B = B^+$  and  $\partial\Omega \cap B = B^0$ . Let  $\hat{B} \Subset B$  and  $\xi \in C_0^\infty(B)$  such that  $\xi > 0$  in  $\hat{B}$  and  $0 \leq \xi \leq 1$  (see Lemma 4.2). Furthermore, assume  $p \in (1, \infty)$ . Then setting

$$B' := \{x' : (x', x_n) \in B\} \subset \mathbb{R}^{n-1},$$

we have for  $u \in C^1(\bar{\Omega})$

$$\begin{aligned} \int_{\partial\Omega \cap B} |\xi u|^p d\sigma &= \int_{B'} |\xi u|^p(x', 0) dx' \\ &= \int_{B'} \left( \left[ - \int_0^{\tilde{x}} \partial_{x_n}(|\xi u|^p)(x', s) ds \right] + \underbrace{|\xi u|^p(x', \tilde{x})}_{=0} \right) dx', \end{aligned}$$

where  $(x', \tilde{x}) \in \partial B \cap (\bar{B}^+ \setminus B^0)$ ,

$$\begin{aligned} &= - \int_{B^+} \left( |u|^p p \xi^{p-1} \xi_{x_n} + \xi^p p |u|^{p-1} \frac{u}{|u|} u_{x_n} \right)(x) dx \\ &\leq C_1 \int_{B^+} (|u|^p + |u|^{p-1} |u_{x_n}|) dx \\ &\leq C_2 \int_{B^+} (|u|^p + |u_{x_n}|^p) dx \\ &\leq C_2 \|u\|_{W^{1,p}(B^+)}^p, \end{aligned}$$

where  $C_2 > 0$  depends on  $p$  and  $\xi$  and we used *Young's inequality*

$$|ab| \leq \frac{1}{p}|a|^p + \frac{1}{q}|b|^q \quad \text{for } a, b \in \mathbb{R}, p, q \in [1, \infty], \frac{1}{p} + \frac{1}{q} = 1,$$

with  $a = u_{x_n}(x)$ ,  $b = |u|^{p-1}(x)$ ,  $q = \frac{p}{p-1}$ . Summing up the previous calculation, we have shown

$$(5.5) \quad \int_{\partial\Omega \cap B} |\xi u|^p d\sigma \leq C_2 \|u\|_{W^{1,p}(B^+)}^p \quad \text{for all } u \in C^1(\bar{\Omega}), p \in (1, \infty).$$

A similar calculation shows that (5.5) also holds for  $p = 1$ .

ii) In the general case of Definition 5.6, let  $B^i = B_{s_i}(x^i)$  such that  $\Phi_i(U_i) \subset B^i$  (with  $\Phi_i, \Psi_i$  from Lemma 5.3 with  $\gamma = \gamma_i$  to flatten the boundary). Then applying (5.5) with  $B = B^i$ ,  $\xi = T_{\Psi_i}(\varphi_i)$ , we obtain with  $u_i = \varphi_i u$  for  $u \in C^1(\bar{\Omega})$

$$\begin{aligned} \int_{\partial\Omega} |u_i|^p d\sigma &= \int_{U'_i} |\varphi_i u|^p(x', \gamma_i(x')) \sqrt{1 + |\nabla \gamma_i(x')|^2} dx' \leq C_3 \int_{(B^i)'} |T_{\Psi_i}(\varphi_i u)|^p(x', 0) dx' \\ &\stackrel{(5.5)}{\leq} C_4 \|T_{\Psi_i} u\|_{W^{1,p}((B^i)^+)}^p \stackrel{\text{Prop. 5.4}}{\leq} C_5 \|u\|_{W^{1,p}(\Omega)}^p. \end{aligned}$$

Hence,

$$\|u\|_{L^p(\partial\Omega)} \leq \sum_{i=1}^N \|u_i\|_{L^p(\partial\Omega)} \leq N \cdot C_5^{\frac{1}{p}} \|u\|_{W^{1,p}(\Omega)} \quad \text{for all } u \in C^1(\bar{\Omega}),$$

with  $C_5$  depending on  $p$  and  $\Omega$ .



iii) By defining  $\text{Tr}(u) := u|_{\partial\Omega}$  for  $u \in C^1(\overline{\Omega})$ , we have

$$\|\text{Tr}(u)\|_{L^p(\partial\Omega)} \leq C_6 \|u\|_{W^{1,p}(\Omega)} \quad \text{for all } u \in C^1(\overline{\Omega})$$

by ii). If  $u \in W^{1,p}(\Omega)$  is arbitrary, as  $\text{Tr}$  is linear in  $u$ , we can show like in part iii) of the proof of Theorem 5.5 that there exist  $(u_l)_{l \in \mathbb{N}} \subset C^1(\overline{\Omega})$  such that  $u_l \rightarrow u$  in  $W^{1,p}(\Omega)$  and  $\text{Tr}(u_l) \rightarrow v$  in  $L^p(\partial\Omega)$  for some  $v \in L^p(\partial\Omega)$ . Hence, defining  $\text{Tr}(u) := v$  the operator  $\text{Tr}: W^{1,p}(\Omega) \rightarrow L^p(\partial\Omega)$  is well defined and satisfies b) with  $C = C_6$ .

iv) If  $u \in W^{1,p}(\Omega) \cap C^0(\overline{\Omega})$  and  $(\tilde{u}_l)_{l \in \mathbb{N}} \subset C^1(\overline{\Omega})$  such that  $\tilde{u}_l \rightarrow u$  in  $W^{1,p}(\Omega)$ , we remark that we can choose  $(\tilde{u}_l)_{l \in \mathbb{N}}$  in the proof of Theorem 4.13 such that  $\tilde{u}_l$  converges to  $u$  in  $C^0(\overline{\Omega})$ . ( $u_i$  is uniformly continuous (compact support),  $w_t \rightarrow u_i$  in  $C^0(\overline{\Omega})$  as  $t \downarrow 0$  since  $w_t$  is a translation and  $\varphi_i = \eta_\varepsilon * w_t \rightarrow w_t$  in  $C^0(\overline{\Omega})$  as  $\varepsilon \downarrow 0$  by Theorem 2.1 (as  $\overline{\Omega} \Subset \mathbb{R}^n \setminus \Gamma_t$ )). Hence,  $\text{Tr}(u) = \lim_{l \rightarrow \infty} \text{Tr}(\tilde{u}_l) = \lim_{l \rightarrow \infty} \tilde{u}_l|_{\partial\Omega} = u|_{\partial\Omega}$ .  $\square$

Next, we characterize  $W_0^{k,p}(\Omega)$  functions in terms of trace zero functions.

**Theorem 5.8.** *Let  $\Omega \subset \mathbb{R}^n$  be a bounded domain with  $\partial\Omega \in C^k$  and assume that  $k \in \mathbb{N}$ ,  $p \in [1, \infty)$ , and  $u \in W^{k,p}(\Omega)$ . Then  $u \in W_0^{k,p}(\Omega)$  if and only if  $\text{Tr}(D^\alpha u) = 0$  for all  $\alpha \in \mathbb{N}_0^n$  with  $|\alpha| \leq k - 1$ . In particular,  $W_0^{1,p}(\Omega) = \{u \in W^{1,p}(\Omega) : \text{Tr}(u) = 0\}$ .*

*Proof.* i) “ $\Rightarrow$ ” for  $k = 1$ : Let  $u \in W_0^{1,p}(\Omega)$ . Then there are  $(u_m)_{m \in \mathbb{N}} \subset C_0^\infty(\Omega)$  with  $u_m \rightarrow u$  in  $W^{1,p}(\Omega)$ . As  $\text{Tr}(u_m) = u_m|_{\partial\Omega} = 0$  and Theorem 5.7 shows

$$\begin{aligned} \|\text{Tr}(u)\|_{L^p(\partial\Omega)} &= \|\text{Tr}(u) - \text{Tr}(u_m)\|_{L^p(\partial\Omega)} = \|\text{Tr}(u - u_m)\|_{L^p(\partial\Omega)} \\ &\leq C \|u - u_m\|_{W^{1,p}(\Omega)} \rightarrow 0 \quad \text{as } m \rightarrow \infty, \end{aligned}$$

we have  $\text{Tr}(u) = 0$  in  $L^p(\partial\Omega)$ .

ii) “ $\Leftarrow$ ” for  $k = 1$ : Assume that  $u \in W^{1,p}(\Omega)$  with  $\text{Tr}(u) = 0$ . Then by Theorems 4.13 and 5.7 there exists  $(u_m)_{m \in \mathbb{N}} \subset C^1(\overline{\Omega})$  such that  $u_m \rightarrow u$  in  $W^{1,p}(\Omega)$  and  $\text{Tr}(u_m) \rightarrow \text{Tr}(u) = 0$  in  $L^p(\partial\Omega)$ . By Definition 5.6 this means  $\text{Tr}(\varphi_i u_m) \rightarrow \text{Tr}(\varphi_i u) = 0$  in  $L^p(\partial\Omega \cap U_i)$  for  $i = 1, \dots, N$ . Hence, fixing  $i \in \{1, \dots, N\}$  and  $\Phi_i, \Psi_i$  from Lemma 5.3 (with  $\gamma = \gamma_i$ ) we have  $v_m := T_{\Psi_i}(\varphi_i u_m) \in C^1(B^+ \cup B^0)$  and  $v := T_{\Psi_i}(\varphi_i u) \in W^{1,p}(B^+)$  with  $\text{Tr}(v_m) \rightarrow \text{Tr}(v) = 0$  in  $L^p(B^0)$  for some ball  $B = B_s(x^i) \subset \mathbb{R}^n$  (see part ii) of the proof of Theorem 5.7), where  $v_m, v$  have compact supports  $K_m, K$  in  $B \cap \overline{B^+}$ .

If we find  $w_m \in C_0^\infty(B^+)$  with  $w_m \rightarrow v$  in  $W^{1,p}(B^+)$ , by Proposition 5.4 there is  $f_i := T_{\Phi_i}(w_m) \in C^1(\Omega)$  with  $\text{supp}(f_i) \subset \Omega \cap U_i$  such that  $\|f_i - \varphi_i u\|_{W^{1,p}(\Omega)} \leq \frac{\delta}{2(N+1)}$ . Then  $\tilde{u} := u - \sum_{i=1}^N \varphi_i u$  has compact support in  $\Omega$  so that by Theorems 4.1 and 2.1 there is  $f_0 \in C_0^\infty(\Omega)$  such that  $\|\tilde{u} - f_0\|_{W^{1,p}(\Omega)} \leq \frac{\delta}{2(N+1)}$ .

Then  $\|u - \sum_{i=0}^N f_i\|_{W^{1,p}(\Omega)} \leq \frac{\delta}{2}$  and  $f := \sum_{i=0}^N f_i \in C^1(\Omega)$  with compact support in  $\Omega$ . Hence, by Theorems 4.1 and 2.1 there is  $g \in C_0^\infty(\Omega)$  such that  $\|g - f\|_{W^{1,p}(\Omega)} \leq \frac{\delta}{2}$  and  $\|u - g\|_{W^{1,p}(\Omega)} \leq \delta$ . Hence,  $u \in W_0^{1,p}(\Omega)$  as  $\delta > 0$  is arbitrary.

iii) It remains to find  $w_m \in C_0^\infty(B^+)$  with  $w_m \rightarrow v$  in  $W^{1,p}(B^+)$ . We have

$$(5.6) \quad \text{Tr}(v_m) \rightarrow \text{Tr}(v) = 0 \text{ in } L^p(B^0) \quad \text{and} \quad v_m \rightarrow v \text{ in } W^{1,p}(B^+)$$

by ii) and Proposition 5.4 and 3.8. As  $v_m \in C^1(B^+ \cup B^0)$  we have for  $x \in B^+ \cup B^0$  with  $B' = \{x' : (x', x_n) \in B\}$  and  $\frac{1}{q} + \frac{1}{p} = 1$ .

$$|v_m(x', x_n)| \leq |v_m(x', 0)| + \int_0^{x_n} |(v_m)_{x_n}(x', t)| dt$$

and

$$\begin{aligned} & \int_{B'} |v_m(x', x_n)|^p dx' \\ & \stackrel{\text{H\"older}}{\leq} 2^p \left( \int_{B'} |v_m(x', 0)|^p dx' + \int_{B'} \left[ \left( \int_0^{x_n} 1^q dt \right)^{\frac{1}{q}} \left( \int_0^{x_n} |\nabla v_m(x', t)|^p dt \right)^{\frac{1}{p}} \right]^p dx' \right) \\ & \stackrel{\text{Fubini}}{\leq} 2^p \left( \|v_m\|_{L^p(B^0)}^p + x_n^{p-1} \int_0^{x_n} \int_{B'} |\nabla v_m(x', t)|^p dx' dt \right) \end{aligned}$$

since  $\frac{p}{q} = p-1$  and  $(a+b)^p \leq 2^{p-1}(a^p + b^p)$  for  $a, b \geq 0$ .

Hence, by (5.6) and the dominated convergence theorem, we obtain as  $m \rightarrow \infty$  (for a subsequence)

$$(5.7) \quad \int_{B'} |v(x', x_n)|^p dx' \leq 2^p x_n^{p-1} \int_0^{x_n} \int_{B'} |\nabla v(x', t)|^p dx' dt \quad \text{for a.e. } x_n > 0$$

since we may extend  $v, v_m$  by 0 to  $\overline{\mathbb{R}_+^n}$  without losing regularity.

Let  $\xi \in C^\infty([0, \infty))$  such that  $\xi \equiv 1$  on  $[0, 1]$  and  $\xi \equiv 0$  on  $[2, \infty)$  and define

$$\xi_m(x) := \xi(mx_n), \quad x \in \overline{B^+}, m \in \mathbb{N},$$

and

$$\tilde{w}_m(x) := v(x)(1 - \xi_m(x)).$$

As  $(\tilde{w}_m)_{x_n} = v_{x_n}(1 - \xi_m) - m v \xi'(mx_n)$  and  $(\tilde{w}_m)_{x_i} = v_{x_i}(1 - \xi_m)$  for  $i = 1, \dots, n-1$ , we have as  $\xi_m = 0$  for  $x_n \geq \frac{2}{m}$

$$\begin{aligned} \int_{B^+} |\nabla \tilde{w}_m - \nabla v|^p dx & \leq C_p \int_{B^+} (\xi_m)^p |\nabla v|^p dx + C_p m^p \|\xi'\|_{L^\infty([0, \infty))}^p \int_0^{\frac{2}{m}} \int_{B'} |v|^p dx' dt \\ & =: A_m + B_m. \end{aligned}$$

As  $\xi_m \neq 0$  only for  $0 \leq x_n < \frac{2}{m}$ , the dominated convergence theorem shows  $A_m \rightarrow 0$  as  $m \rightarrow \infty$ . Using (5.7), we obtain

$$\begin{aligned} B_m & \leq C \cdot m^p \int_0^{\frac{2}{m}} \left[ t^{p-1} \int_0^t \int_{B'} |\nabla v|^p(x', s) dx' ds \right] dt \\ & \leq C \cdot m^p \left( \int_0^{\frac{2}{m}} t^{p-1} dt \right) \left( \int_0^{\frac{2}{m}} \int_{B'} |\nabla v|^p(x', s) dx' ds \right) \\ & \leq \tilde{C} \int_0^{\frac{2}{m}} \int_{B'} |\nabla v|^p dx' ds \rightarrow 0 \quad \text{as } m \rightarrow \infty \end{aligned}$$

by the dominated convergence theorem. Hence,  $\nabla \tilde{w}_m \rightarrow \nabla v$  in  $L^p(B^+)$  and, as obviously  $\tilde{w}_m \rightarrow v$  in  $L^p(B^+)$ , we have  $\tilde{w}_m \rightarrow v$  in  $W^{1,p}(B^+)$ . As  $\tilde{w}_m = 0$  for  $x_m \in [0, \frac{1}{m})$  and  $\text{supp } \tilde{w}_m \subset \text{supp } v$ , we have  $\text{supp } \tilde{w}_m \Subset B^+$ . Hence,  $w_m := \eta_{\varepsilon_m} * \tilde{w}_m \in C_0^\infty(B^+)$  satisfies  $w_m \rightarrow v$  in  $W^{1,p}(B^+)$  for  $\varepsilon_m \downarrow 0$  chosen appropriately (by Theorems 4.1 and 2.1). Hence, ii) shows  $u \in W_0^{1,p}(\Omega)$ .

iv) We now prove the claim for all  $k \in \mathbb{N}$  with  $k \geq 2$ . If  $u \in W_0^{k,p}(\Omega)$ , then  $D^\alpha u \in W_0^{1,p}(\Omega)$  for all  $|\alpha| \leq k-1$  by Proposition 3.8 a) and since  $D^\alpha \varphi \in C_0^\infty(\Omega)$  for  $\varphi \in C_0^\infty(\Omega)$ . Then the case  $k=1$  proves “ $\Rightarrow$ ”.

For “ $\Leftarrow$ ”, the case  $k=1$  implies  $D^\alpha u \in W_0^{1,p}(\Omega)$  for all  $|\alpha| \leq k-1$ . Hence, there exist  $(f_m)_{m \in \mathbb{N}}, (g_m)_{m \in \mathbb{N}} \subset C_0^\infty(\Omega)$  such that  $f_m \rightarrow u$  and  $g_m \rightarrow u_{x_n}$  in  $W^{1,p}(\Omega)$  as  $m \rightarrow \infty$ . Assuming  $\Omega \cap U_i = B^+$  and  $\partial\Omega \cap U_i = B^0$  for some Ball  $B$ ,  $g_m$  is 0 in a neighborhood of  $B^0$ . Hence,

$$G_m(x) := \int_0^{x_n} g_m(x', t) dt$$

satisfies  $(G_m)_{x_n} = g_m$  and  $G_m \in C_0^\infty(\Omega \cap \overline{U}_i) = C_0^\infty(\overline{B^+} \setminus B^0)$ . As  $f_m \in C_0^\infty(\Omega)$  we have  $f_m(x) = \int_0^{x_n} (f_m)_{x_n}(x', t) dt$  and hence

$$\|f_m - G_m\|_{L^p(\Omega \cap U_i)} \leq C \|(f_m)_{x_n} - g_m\|_{L^p(\Omega \cap U_i)}$$

with some  $C$  depending on  $p$  and  $U_i$  by Hölder's inequality. Since  $g_m \rightarrow u_{x_n}$  and  $(f_m)_{x_n} \rightarrow u_{x_n}$  in  $L^p(\Omega)$ , we see that  $D^\alpha G_m \rightarrow D^\alpha u$  in  $L^p(\Omega \cap U_i)$  for all  $|\alpha| \leq 2$  with  $\alpha_n \geq 1$  and  $G_m \rightarrow u$  in  $L^p(\Omega \cap U_i)$  as  $m \rightarrow \infty$ . Iterating this argument with  $u_{x_i}, i = 1, \dots, n-1$  and using an induction on  $k$  and the arguments of ii), we see that  $G_m \rightarrow u$  in  $W^{k,p}(\Omega \cap U_i)$  and hence  $u \in W_0^{k,p}(\Omega)$  (like in ii)).  $\square$

## Chapter 6

# Embeddings and Sobolev Inequalities

We ask the question if  $u \in W^{k,p}(\Omega)$  automatically belongs to some other function spaces. The answer is *yes*, but we will see that to which spaces  $u$  belongs depends on  $p$ , e.g. for  $k = 1$  and  $p < n$ ,  $p = n$  or  $p > n$ .

More precisely we ask whether  $X = W^{k,p}(\Omega)$  is embedded into a space  $Y$  in the following sense.

**Definition 6.1.** Let  $X, Y$  be Banach spaces with  $X \subset Y$ .

a) We say that  $X$  is *continuously embedded into*  $Y$  if there is  $C > 0$  such that

$$\|u\|_Y \leq C \|u\|_X \quad \text{for all } u \in X.$$

b) We say that  $X$  is *compactly embedded into*  $Y$  if it is continuously embedded into  $Y$  and any bounded sequence in  $X$  is *precompact in*  $Y$ , i.e. for any  $(u_m)_{m \in \mathbb{N}} \subset X$  with  $\|u_m\|_X \leq M$  for all  $m \in \mathbb{N}$ , there is a subsequence  $(u_{m_j})_{j \in \mathbb{N}}$  and  $u \in Y$  such that  $\|u_{m_j} - u\|_Y \rightarrow 0$  as  $j \rightarrow \infty$ .

The main tool for studying such embeddings will be Sobolev-type inequalities.

### 6.1 Embeddings into $L^q(\Omega)$ Spaces

Let us assume  $p \in [1, n)$  and ask the question for which  $q \in [1, \infty)$  there exists a constant  $C > 0$  such that

$$(6.1) \quad \|u\|_{L^q(\mathbb{R}^n)} \leq C \|\nabla u\|_{L^p(\mathbb{R}^n)} \quad \text{for all } u \in C_0^\infty(\mathbb{R}^n).$$

*Motivation.* We first demonstrate that if (6.1) holds, then  $q$  has to have a specific form: To this end, let  $u \in C_0^\infty(\Omega)$  with  $u \not\equiv 0$  and for  $\lambda > 0$

$$u_\lambda(x) := u(\lambda x) \quad \text{for all } x \in \mathbb{R}^n.$$

Then the transformation rule implies

$$\begin{aligned} \int_{\mathbb{R}^n} |u_\lambda(x)|^q dx &= \int_{\mathbb{R}^n} |u(\lambda x)|^q dx = \frac{1}{\lambda^n} \int_{\mathbb{R}^n} |u(y)|^q dy, \\ \int_{\mathbb{R}^n} |\nabla u_\lambda(x)|^p dx &= \lambda^p \int_{\mathbb{R}^n} |(\nabla u)(\lambda x)|^p dx = \frac{\lambda^p}{\lambda^n} \int_{\mathbb{R}^n} |\nabla u(y)|^p dy. \end{aligned}$$

If (6.1) holds for any  $\lambda > 0$ , then

$$\lambda^{-\frac{n}{q}} \|u\|_{L^q(\mathbb{R}^n)} = \|u\lambda\|_{L^q(\mathbb{R}^n)} \leq C \|\nabla u\lambda\|_{L^p(\mathbb{R}^n)} = C \lambda^{1-\frac{n}{p}} \|\nabla u\|_{L^p(\mathbb{R}^n)}$$

and therefore

$$(6.2) \quad \|u\|_{L^q(\mathbb{R}^n)} \leq C \lambda^{1-\frac{n}{p}+\frac{n}{q}} \|\nabla u\|_{L^p(\mathbb{R}^n)}.$$

But if  $1 - \frac{n}{p} + \frac{n}{q} \neq 0$ , then sending  $\lambda$  to either 0 or  $\infty$  in (6.2) yields  $u \equiv 0$ , a contradiction.

Hence, if (6.1) is satisfied, then necessarily we must have  $\frac{1}{q} = \frac{1}{p} - \frac{1}{n}$  and  $q = \frac{np}{n-p}$ . This motivates the following definition.

**Definition 6.2.** If  $p \in [1, n)$ , then  $p^* := \frac{np}{n-p}$  is the *Sobolev conjugate* of  $p$ . In particular,  $\frac{1}{p^*} = \frac{1}{p} - \frac{1}{n}$ .

We next prove that (6.1) is in fact true for  $q = p^*$ .

**Theorem 6.3** (Gagliardo-Nirenberg-Sobolev inequality). *Assume that  $p \in [1, n)$ . Then there exists  $C > 0$ , depending only on  $p$  and  $n$ , such that*

$$(6.3) \quad \|u\|_{L^{p^*}(\mathbb{R}^n)} \leq C \|\nabla u\|_{L^p(\mathbb{R}^n)}, \quad \text{for all } u \in C_0^1(\mathbb{R}^n).$$

Moreover, we have  $W^{1,p}(\mathbb{R}^n) \subset L^{p^*}(\mathbb{R}^n)$  and (6.3) holds for all  $u \in W^{1,p}(\mathbb{R}^n)$ .

*Remark 6.4.* We need that  $u$  in (6.3) has compact support, as  $u \equiv 1$  shows, but  $C$  does not depend on the size of the support.

*Proof of Theorem 6.3.* i) Let  $u \in C_0^1(\mathbb{R}^n)$  and  $p = 1$ , whence  $p^* = \frac{n}{n-1}$ . Since  $\text{supp}(u)$  is compact, we have for all  $x \in \mathbb{R}^n$  and  $i \in \{1, \dots, n\}$

$$u(x) = \int_{-\infty}^{x_i} u_{x_i}(x_1, \dots, x_{i-1}, y_i, x_{i+1}, \dots, x_n) dy_i$$

and

$$|u(x)| \leq \int_{-\infty}^{\infty} |\nabla u(x_1, \dots, x_{i-1}, y_i, x_{i+1}, \dots, x_n)| dy_i.$$

Hence,

$$|u(x)|^{\frac{n}{n-1}} \leq \prod_{i=1}^n \left( \int_{-\infty}^{\infty} |\nabla u(x_1, \dots, x_{i-1}, y_i, x_{i+1}, \dots, x_n)| dy_i \right)^{\frac{1}{n-1}}.$$

Integrating this with respect to  $x_1$  and using the general Hölder inequality (2.1 viii) with  $p_k = n-1, k = 1, \dots, n-1$ )

$$\begin{aligned} \int_{-\infty}^{\infty} |u|^{\frac{n}{n-1}}(x) dx_1 &\leq \int_{-\infty}^{\infty} \prod_{i=1}^n \left( \int_{-\infty}^{\infty} |\nabla u| dy_i \right)^{\frac{1}{n-1}} dx_1 \\ &= \left( \int_{-\infty}^{\infty} |\nabla u| dy_1 \right)^{\frac{1}{n-1}} \int_{-\infty}^{\infty} \prod_{i=2}^n \left( \int_{-\infty}^{\infty} |\nabla u| dy_i \right)^{\frac{1}{n-1}} dx_1 \\ &\leq \left( \int_{-\infty}^{\infty} |\nabla u| dy_1 \right)^{\frac{n}{n-1}} \prod_{i=2}^n \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |\nabla u| dy_i dx_1 \right)^{\frac{1}{n-1}}. \end{aligned}$$

Integrating with respect to  $x_2$  and using again the general Hölder inequality, we get

$$\begin{aligned}
& \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |u(x)|^{\frac{n}{n-1}} dx_1 dx_2 \\
& \leq \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |\nabla u| dy_2 dx_1 \right)^{\frac{1}{n-1}} \\
& \quad \cdot \left[ \int_{-\infty}^{\infty} \left( \int_{-\infty}^{\infty} |\nabla u| dy_1 \right)^{\frac{1}{n-1}} \prod_{i=3}^n \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |\nabla u| dx_1 dy_i \right)^{\frac{1}{n-1}} dx_2 \right] \\
& \leq \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |\nabla u| dy_2 dx_1 \right)^{\frac{1}{n-1}} \\
& \quad \cdot \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |\nabla u| dy_1 dx_2 \right)^{\frac{1}{n-1}} \prod_{i=3}^n \left( \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |\nabla u| dx_1 dx_2 dy_i \right)^{\frac{1}{n-1}}
\end{aligned}$$

Continuing like this and integrating with respect to  $x_3, \dots, x_n$  we finally have

$$\begin{aligned}
(6.4) \quad \int_{\mathbb{R}^n} |u(x)|^{\frac{n}{n-1}} dx & \leq \prod_{i=1}^n \left( \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} |\nabla u| dx_1 \dots dy_i \dots dx_n \right)^{\frac{1}{n-1}} \\
& = \left( \int_{\mathbb{R}^n} |\nabla u(x)| dx \right)^{\frac{n}{n-1}}
\end{aligned}$$

which establishes (6.3) for  $p = 1$  with  $C = 1$ .

- ii) Let  $p \in (1, n)$  and  $u \in C_0^1(\mathbb{R}^n)$ . For  $\gamma > 1$ ,  $v := |u|^\gamma \in C_0^1(\mathbb{R}^n)$  and by (6.4) applied to  $v$  we have by the Hölder inequality

$$\begin{aligned}
(6.5) \quad \left( \int_{\mathbb{R}^n} |u|^{\frac{\gamma n}{n-1}} \right)^{\frac{n-1}{n}} & \leq \int_{\mathbb{R}^n} |\nabla(|u|^\gamma)| dx = \int_{\mathbb{R}^n} \gamma |u|^{\gamma-1} |\nabla u| dx \\
& \leq \gamma \left( \int_{\mathbb{R}^n} |u|^{(\gamma-1)\frac{p}{p-1}} dx \right)^{\frac{p-1}{p}} \left( \int_{\mathbb{R}^n} |\nabla u|^p dx \right)^{\frac{1}{p}}.
\end{aligned}$$

Choosing  $\gamma := \frac{p(n-1)}{n-p} > 1$ , we have  $\frac{\gamma n}{n-1} = (\gamma-1)\frac{p}{p-1}$  and hence

$$\frac{\gamma n}{n-1} = \frac{(np-p) + (p-n)}{n-p} \cdot \frac{p}{p-1} = \frac{np}{n-p} = p^*.$$

Thus, in view of  $\frac{n-1}{n} - \frac{p-1}{p} = \frac{1}{p} - \frac{1}{n} = \frac{1}{p^*}$ , (6.5) becomes (6.3) for  $C = \gamma$ .

- iii) As  $W^{1,p}(\mathbb{R}^n) = W_0^{1,p}(\mathbb{R}^n)$  by Corollary 4.14 for  $u \in W^{1,p}(\mathbb{R}^n)$  there is  $(u_m)_{m \in \mathbb{N}} \subset C_0^\infty(\mathbb{R}^n)$  such that  $u_m \rightarrow u$  in  $W^{1,p}(\mathbb{R}^n)$ . Hence,  $\nabla u_m \rightarrow \nabla u$  in  $L^p(\mathbb{R}^n)$  and, as (6.3) holds for any  $u_m$ , in the limit  $l \rightarrow \infty$  we conclude by Fatou's lemma that  $u$  satisfies (6.3) since  $u_{m_l} \rightarrow u$  a.e. in  $\mathbb{R}^n$ . As (6.3) therefore holds for all  $u \in W^{1,p}(\mathbb{R}^n)$ ,  $W^{1,p}(\mathbb{R}^n)$  is continuously embedded into  $L^{p^*}(\mathbb{R}^n)$ .  $\square$

Using the previous result, we get a corresponding result on bounded domains.

**Theorem 6.5** (Embeddings for  $W^{1,p}(\Omega)$ ,  $p < n$ ). *Let  $\Omega \subset \mathbb{R}^n$  be a bounded domain with  $\partial\Omega \in C^1$  and  $p \in [1, n)$ . Then  $W^{1,p}(\Omega)$  is continuously embedded into  $L^q$  for all  $q \in [1, p^*]$ . More precisely, for any  $q \in [1, p^*]$  there is  $C > 0$  depending on  $p, q, n$  and  $\Omega$  such that*

$$(6.6) \quad \|u\|_{L^q(\Omega)} \leq C \|\nabla u\|_{W^{1,p}(\Omega)} \quad \text{for all } u \in W^{1,p}(\Omega).$$

*Proof.* Since  $\partial\Omega \in C^1$ , by Theorem 5.5 there exists  $v := E(u) \in W^{1,p}(\mathbb{R}^n)$  such that  $v = u$  a.e. in  $\Omega$  and  $\|v\|_{W^{1,p}(\mathbb{R}^n)} \leq C_1 \|u\|_{W^{1,p}(\Omega)}$  with  $C_1 > 0$  depending only on  $p$  and  $\Omega$ . Then by 6.3 we have  $v \in L^{p^*}(\mathbb{R}^n)$  and

$$\|u\|_{L^{p^*}(\Omega)} = \|v\|_{L^{p^*}(\Omega)} \leq \|v\|_{L^{p^*}(\mathbb{R}^n)} \leq C_2 \|\nabla v\|_{L^p(\mathbb{R}^n)} \leq C_1 C_2 \|u\|_{W^{1,p}(\Omega)}$$

where  $C_2$  is the constant from (6.3) (depending on  $p$  and  $n$ ). This shows the claim for  $q = p^*$ . As  $\Omega$  is bounded, Hölder's inequality implies that  $u \in L^q(\Omega)$  for  $q \in [1, p^*)$  with

$$(6.7) \quad \begin{aligned} \|u\|_{L^q(\Omega)} &\leq \left[ \left( \int_{\Omega} 1^{\frac{p^*}{p^*-q}} dx \right)^{\frac{p^*-q}{p^*}} \cdot \left( \int_{\Omega} u^q \frac{p^*}{q} \right)^{\frac{q}{p^*}} \right]^{\frac{1}{q}} \\ &= |\Omega|^{\frac{p^*-q}{p^*q}} \|u\|_{L^{p^*}(\Omega)} \leq |\Omega|^{\frac{p^*-q}{p^*q}} C_1 C_2 \|u\|_{W^{1,p}(\Omega)}. \end{aligned} \quad \square$$

For  $W_0^{1,p}(\Omega)$ , we get these embeddings without assumptions on  $\partial\Omega$ .

**Theorem 6.6.** *Let  $\Omega \subset \mathbb{R}^n$  be a bounded domain and  $p \in [1, n)$ . Then for any  $q \in [1, p^*]$  there exists  $C > 0$  depending only on  $p, q, n$  and  $\Omega$  such that*

$$(6.8) \quad \|u\|_{L^q(\Omega)} \leq C \|\nabla u\|_{L^p(\Omega)} \quad \text{for all } u \in W_0^{1,p}(\Omega).$$

*In particular,  $W_0^{1,p}(\Omega)$  is continuously embedded into  $L^q(\Omega)$ .*

*Proof.* Since  $u \in W_0^{1,p}(\Omega)$ , there exist  $u_m \in C_0^\infty(\Omega)$  such that  $u_m \rightarrow u$  in  $W^{1,p}(\Omega)$ . We extend  $u_m$  by 0 on  $\mathbb{R}^n \setminus \Omega$  and have  $u_m \in C_0^\infty(\mathbb{R}^n)$  so that  $u_m$  satisfies (6.3) for all  $m \in \mathbb{N}$ . In particular,  $\|u_m - u_j\|_{L^{p^*}(\mathbb{R}^n)} \leq C \|\nabla u_m - \nabla u_j\|_{L^p(\mathbb{R}^n)}$  for all  $m, j$  so that  $(u_m)_m$  is a Cauchy sequence in  $L^{p^*}(\Omega)$  with limit  $v$ . As  $u_{m_j} \rightarrow u$  a.e. in  $\Omega$ , we conclude that  $v = u$ ,  $u_m \rightarrow u$  in  $L^{p^*}(\Omega)$  and

$$\|u\|_{L^{p^*}(\Omega)} = \lim_{m \rightarrow \infty} \|u_m\|_{L^{p^*}(\Omega)} \leq C \lim_{m \rightarrow \infty} \|\nabla u_m\|_{L^p(\Omega)} = C \|\nabla u\|_{L^p(\Omega)}$$

with  $C$  from (6.3). This shows (6.8) for  $q = p^*$ . For  $q \in [1, p^*)$ , we have  $\|u\|_{L^q(\Omega)} \leq |\Omega|^{\frac{p^*-q}{p^*q}} \|u\|_{L^{p^*}(\Omega)}$  (see (6.7)) and the claim follows.  $\square$

As  $p^* = \frac{np}{n-p} > \frac{np}{n} = p$ , we may choose  $q = p$  in (6.8) and have the following Corollary.

**Corollary 6.7** (Poincaré-inequality). *Let  $\Omega \subset \mathbb{R}^n$  be a bounded domain and  $p \in [1, \infty]$ . Then we have the Poincaré-inequality*

$$(6.9) \quad \|u\|_{L^p(\Omega)} \leq C \|\nabla u\|_{L^p(\Omega)} \quad \text{for all } u \in W_0^{1,p}(\Omega),$$

*where  $C > 0$  only depends on  $p, n$ , and  $\Omega$ .*

*In particular, the norm  $\|\nabla u\|_{L^p(\Omega)}$  is equivalent to  $\|u\|_{W^{1,p}(\Omega)}$  in  $W_0^{1,p}(\Omega)$ .*

*Proof.* For  $p \in [1, n)$ , (6.9) immediately follows from (6.8). For fixed  $p \in [n, \infty)$  there is  $\tilde{p} \in [1, n)$  such that  $\tilde{p}^* = \frac{n\tilde{p}}{n-\tilde{p}} > p$  since  $\tilde{p}^* \rightarrow \infty$  as  $\tilde{p} \uparrow n$ . Hence, as  $\tilde{p} < n \leq p$ , we have by (6.8) (with  $q := p$ )

$$(6.10) \quad \|u\|_{L^p(\Omega)} \leq C \|\nabla u\|_{L^{\tilde{p}}(\Omega)} \leq C |\Omega|^{\frac{p-\tilde{p}}{p\tilde{p}}} \|\nabla u\|_{L^p(\Omega)} \quad \text{for all } u \in W_0^{1,p}(\Omega).$$

Here we used that Hölder's inequality implies (see (6.8))  $\|v\|_{L^{\tilde{p}}(\Omega)} \leq |\Omega|^{\frac{p-\tilde{p}}{p\tilde{p}}} \|v\|_{L^p(\Omega)}$  for all  $v \in L^p(\Omega)$  so that  $u \in W^{1,\tilde{p}}(\Omega)$  and, since some  $(u_m)_{m \in \mathbb{N}} \subset C_0^\infty(\Omega)$  satisfies  $u_m \rightarrow u$  in  $W^{1,p}(\Omega)$  it therefore also satisfies  $u_m \rightarrow u$  in  $W^{1,\tilde{p}}(\Omega)$ . Hence,  $u \in W_0^{1,\tilde{p}}(\Omega)$  and the application of (6.8) in (6.10) is justified.

For  $p = \infty$  and  $u \in W_0^{1,\infty}(\Omega)$ , there is  $(u_m)_{m \in \mathbb{N}} \subset C_0^\infty(\Omega)$  such that  $u_m \rightarrow u$  in  $W^{1,\infty}(\Omega)$ . Since  $\Omega \subset (-b, b)^n$ , for each  $m \in \mathbb{N}$  we have

$$|u_m(x)| = |u_m(x', x_n)| = \left| \underbrace{u_m(x', -b)}_{=0} + \int_{-b}^{x_n} (u_m)_{x_n}(x', t) dt \right| \leq 2b \|\nabla u_m\|_{L^\infty(\Omega)}.$$

Hence,  $\|u_m\|_{L^\infty(\Omega)} \leq 2b \|\nabla u_m\|_{L^\infty(\Omega)}$  for all  $m \in \mathbb{N}$  and taking  $m \rightarrow \infty$  we conclude that (6.9) holds for  $u$  with  $C := 2b$  depending only on  $\Omega$ .  $\square$

Next, let us assume  $p = n$ . As  $p^* \rightarrow \infty$  for  $p \uparrow n$ , we might expect  $W^{1,n}(\Omega) \subset L^\infty(\Omega)$ , but this is false in general for  $n \geq 2$ .

**Proposition 6.8** (Embeddings for  $W^{1,n}(\Omega)$ ). *Let  $\Omega \subset \mathbb{R}^n$  be a bounded domain and  $q \in [1, \infty)$ .*

a) *If  $\partial\Omega \in C^1$ , then  $W^{1,n}(\Omega)$  is continuously embedded into  $L^q(\Omega)$  and*

$$\|u\|_{L^q(\Omega)} \leq C \|u\|_{W^{1,n}(\Omega)} \quad \text{for all } u \in W^{1,n}(\Omega)$$

b)  *$W_0^{1,n}(\Omega)$  is continuously embedded to  $L^q(\Omega)$  and, with  $C$  depending on  $q, n, \Omega$ , we have*

$$\|u\|_{L^q(\Omega)} \leq C \|\nabla u\|_{L^n(\Omega)} \quad \text{for all } u \in W_0^{1,n}(\Omega).$$

c) *If  $n = 1$  and  $\Omega = (a, b) \subset \mathbb{R}$  with  $-\infty < a < b < +\infty$ , then  $W^{1,1}((a, b)) \subset L^\infty((a, b))$  and there is  $C$  depending on  $b - a$  such that*

$$\|u\|_{L^\infty((a,b))} \leq C \|u\|_{W^{1,1}((a,b))} \quad \text{for all } u \in W^{1,1}((a, b))$$

and

$$\|u\|_{L^\infty((a,b))} \leq \|u'\|_{L^1((a,b))} \quad \text{for all } u \in W_0^{1,1}((a, b)).$$

*Proof.* Exercise.  $\square$

**Remark 6.9.** If  $n = 1$  and  $\Omega = (a, b)$  is bounded, in fact  $W^{1,1}((a, b))$  and  $W_0^{1,1}((a, b))$  are both continuously embedded to  $C^0([a, b])$ . This can be proved with Proposition 6.8 c) (with the choice of a continuous representative of  $u \in W^{1,1}((a, b))$ ). For  $n \geq 2$ ,  $W^{1,n}(B_1(0)) \not\subset L^\infty(B_1(0))$ , as e.g.  $u(x) = \ln(\ln(1 + \frac{1}{|x|}))$  satisfies  $u \in W^{1,n}(B_1(0))$  and  $u \notin L^\infty(B_1(0))$  (see Exercise).

## 6.2 Embeddings into Hölder Spaces

If  $\Omega \subset \mathbb{R}^n$  is open and  $u: \Omega \rightarrow \mathbb{R}$  satisfies

$$(6.12) \quad |u(x) - u(y)| \leq M |x - y|^\gamma \quad \text{for all } x, y \in \Omega$$

with some  $M > 0$  and  $\gamma \in (0, 1)$ ,  $u$  is called *Hölder continuous with exponent  $\gamma$* . Note that  $\gamma = 1$  corresponds to *Lipschitz continuous* functions. We define the corresponding function spaces.



**Definition 6.10.** Let  $\Omega \subset \mathbb{R}^n$  be open.

a) For  $u \in C_b^0(\overline{\Omega}) := C^0(\overline{\Omega}) \cap L^\infty(\Omega)$  we define  $\|u\|_{C^0(\overline{\Omega})} := \sup_{x \in \Omega} |u(x)|$ . For  $\Omega$  bounded we have  $C_b^0(\overline{\Omega}) = C^0(\overline{\Omega})$ .

b) For  $\gamma \in (0, 1]$  and  $u: \overline{\Omega} \rightarrow \mathbb{R}$  the  $\gamma$ -Hölder seminorm is defined as

$$[u]_{C^{0,\gamma}(\overline{\Omega})} := \sup_{x,y \in \Omega, x \neq y} \frac{|u(x) - u(y)|}{|x - y|^\gamma},$$

and the  $\gamma$ -Hölder norm is defined as

$$\|u\|_{C^{0,\gamma}(\overline{\Omega})} := \|u\|_{C^0(\overline{\Omega})} + [u]_{C^{0,\gamma}(\overline{\Omega})}.$$

c) For  $k \in \mathbb{N}_0$  and  $\gamma \in (0, 1]$ , we define the Hölder space

$$C^{k,\gamma}(\overline{\Omega}) := \{u \in C^k(\overline{\Omega}) : \|u\|_{C^{k,\gamma}(\overline{\Omega})} < \infty\},$$

where

$$\|u\|_{C^{k,\gamma}(\overline{\Omega})} := \sum_{|\alpha| \leq k} \|D^\alpha u\|_{C^0(\overline{\Omega})} + \sum_{|\alpha|=k} [D^\alpha u]_{C^{0,\gamma}(\overline{\Omega})}.$$

(In case of  $\Omega$  unbounded one also writes  $C_b^{k,\gamma}(\overline{\Omega})$  instead of  $C^{k,\gamma}(\overline{\Omega})$  to indicate that the functions are in  $C_b^k(\overline{\Omega}) = \{u \in C^k(\overline{\Omega}) : D^\alpha u \in L^\infty(\Omega), \text{ for all } |\alpha| \leq k\}$ )

The spaces  $C^{k,\gamma}(\overline{\Omega})$  have a good mathematical structure and are also Banach spaces.

**Proposition 6.11.** Let  $\Omega \subset \mathbb{R}^n$  be open,  $k \in \mathbb{N}_0$ , and  $\gamma \in (0, 1]$ . Then  $C^{k,\gamma}(\overline{\Omega})$  is a Banach space.

*Proof.* It is not difficult to verify that  $\|\cdot\|_{C^{k,\gamma}(\overline{\Omega})}$  is a norm on  $C^{k,\gamma}(\overline{\Omega})$ . To show that  $C^{k,\gamma}(\overline{\Omega})$  is complete, assume that  $(u_m)_{m \in \mathbb{N}} \subset C^{k,\gamma}(\overline{\Omega})$  is a Cauchy sequence. Then it is also a Cauchy sequence in  $C_b^k(\overline{\Omega})$  and hence  $u_m \rightarrow u$  as  $m \rightarrow \infty$  in  $C_b^k(\overline{\Omega})$  with some  $u \in C_b^k(\overline{\Omega})$ . As  $D^\alpha u_m$  satisfy (6.12) for all  $m \in \mathbb{N}$  with  $M := \sup_{m \in \mathbb{N}} \|u_m\|_{C^{k,\gamma}(\overline{\Omega})}$  for any  $|\alpha| = k$ , taking  $m \rightarrow \infty$ , we conclude that  $D^\alpha u$  also satisfies (6.12) with the same  $M$ . Hence,  $u \in C^{k,\gamma}(\overline{\Omega})$ .  $\square$

We next study the case  $u \in W^{1,p}(\Omega)$  with  $p \in (n, \infty)$  and show that  $u$  is Hölder continuous after possibly being redefined on a set of measure zero. Again an inequality for  $W^{1,p}(\mathbb{R}^n)$  functions will be the basis.

**Theorem 6.12** (Morrey's inequality). Assume that  $p \in (n, \infty]$  and  $\gamma := 1 - \frac{n}{p}$  (with  $\gamma = 1$  in case of  $p = \infty$ ). Then there is  $C > 0$  depending only on  $p$  and  $n$  such that

$$(6.13) \quad \|u\|_{C^{0,\gamma}(\mathbb{R}^n)} \leq C \|u\|_{W^{1,p}(\mathbb{R}^n)} \quad \text{for all } u \in C^1(\mathbb{R}^n) \cap W^{1,p}(\mathbb{R}^n).$$

*Proof.* i) The case  $p = \infty$  is immediate. For  $u \in C^1(\mathbb{R}^n) \cap W^{1,\infty}(\mathbb{R}^n)$  we have

$$|u(x) - u(y)| \leq \|\nabla u\|_{L^\infty(\mathbb{R}^n)} |x - y| \quad \text{for all } x, y \in \mathbb{R}^n$$

by the mean value theorem. Hence,

$$\|u\|_{C^{0,1}(\mathbb{R}^n)} = \|u\|_{C^0(\mathbb{R}^n)} + [u]_{C^{0,1}(\mathbb{R}^n)} \leq \|u\|_{L^\infty(\mathbb{R}^n)} + \|\nabla u\|_{L^\infty(\mathbb{R}^n)} \leq \|u\|_{W^{1,\infty}(\mathbb{R}^n)}$$

- ii) Let  $u \in C^1(\mathbb{R}^n)$  and  $B_r(x) \subset \mathbb{R}^n$  a ball. Then there is  $C_1 > 0$  depending only on  $n$  such that

$$(6.14) \quad \frac{1}{|B_r(x)|} \int_{B_r(x)} |u(y) - u(x)| \, dy \leq C_1 \int_{B_r(x)} \frac{|\nabla u(y)|}{|y - x|^{n-1}} \, dy.$$

In order to prove this, we fix  $w \in \partial B_1(0)$ . Then for  $s \in (0, r)$  we have

$$|u(x + sw) - u(x)| = \left| \int_0^s \frac{d}{dt} u(x + tw) \, dt \right| = \left| \int_0^s \nabla u(x + tw) \cdot w \, dt \right| \stackrel{|w|=1}{\leq} \int_0^s |\nabla u(x + tw)| \, dt$$

Hence, integrating and using polar coordinates (see 2.4), we have

$$\begin{aligned} \int_{\partial B_1(0)} |u(x + sw) - u(x)| \, d\sigma(w) &\stackrel{\text{Fubini}}{\leq} \int_0^s \int_{\partial B_1(0)} |\nabla u(x + tw)| \, d\sigma(w) \, dt \\ &= \int_0^s t^{n-1} \int_{\partial B_1(0)} \frac{|\nabla u(x + tw)|}{t^{n-1}} \, d\sigma(w) \, dt \\ &\stackrel{|w|=1}{=} \int_0^s t^{n-1} \int_{\partial B_1(0)} \frac{|\nabla u(x + tw)|}{|x - (x + tw)|^{n-1}} \, d\sigma(w) \, dt \\ &= \int_0^s \int_{B_t(x)} \frac{|\nabla u(y)|}{|x - y|^{n-1}} \, d\sigma(y) \, dt \end{aligned}$$

and by using 2.4 and applying the transformation  $y = x + tw$  we get

$$= \int_{B_s(x)} \frac{|\nabla u(y)|}{|x - y|^{n-1}} \, dy \stackrel{s \leq r}{\leq} \int_{B_r(x)} \frac{|\nabla u(y)|}{|x - y|^{n-1}} \, dy.$$

Multiplying by  $s^{n-1}$  and integrating, we obtain from 2.4

$$\begin{aligned} \int_{B_r(x)} |u(y) - u(x)| \, dy &\stackrel{2.4}{=} \int_0^r s^{n-1} \int_{\partial B_1(0)} |u(x + sw) - u(x)| \, d\sigma(w) \, ds \\ &\leq \frac{r^n}{n} \int_{B_r(x)} \frac{|\nabla u(y)|}{|x - y|^{n-1}} \, dy. \end{aligned}$$

Dividing by  $|B_r(x)| = c_n r^n$ , we obtain (6.14)

- iii) Now assume that  $u \in C^1(\mathbb{R}^n) \cap W^{1,p}(\mathbb{R}^n)$  with  $p \in (n, \infty)$ . Since the choice of  $p$  implies  $\frac{n-1}{n} = 1 - \frac{1}{n} < \frac{p-1}{p}$ , we have  $\frac{(n-1)p}{p-1} < 1$  and

$$\int_{B_1(x)} |x - y|^{-\frac{(n-1)p}{p-1}} \, dy \stackrel{2.4}{=} \omega_n \int_0^1 r^{-\frac{(n-1)p}{p-1}} \cdot r^{n-1} \, dr = C_2(n, p) < \infty \quad \text{for all } x \in \mathbb{R}^n$$

Hence, we obtain for  $x \in \mathbb{R}^n$  with  $q = \frac{p}{p-1}$  ( $\frac{1}{p} + \frac{1}{q} = 1$ )

$$\begin{aligned} |u(x)| &= \frac{1}{|B_1(x)|} \int_{B_1(x)} |u(x)| \, dy \leq \frac{1}{|B_1(x)|} \left( \int_{B_1(x)} |u(x) - u(y)| \, dy + \int_{B_1(x)} |u(y)| \, dy \right) \\ &\stackrel{(6.14), \text{H\"older}}{\leq} C_1 \int_{B_1(x)} \frac{|\nabla u(y)|}{|x - y|^{n-1}} \, dy + \frac{1}{|B_1(x)|} \left( \int_{B_1(x)} 1^q \, dy \right)^{\frac{1}{q}} \left( \int_{B_1(x)} |u(y)|^p \, dy \right)^{\frac{1}{p}} \\ &\stackrel{\text{H\"older}}{\leq} C_1 \left( \int_{B_1(x)} |\nabla u(y)|^p \, dy \right)^{\frac{1}{p}} \left( \int_{B_1(x)} |x - y|^{-\frac{(n-1)p}{p-1}} \, dy \right)^{\frac{p-1}{p}} + |B_1(x)|^{-\frac{1}{p}} \|u\|_{L^p(\mathbb{R}^n)} \\ &\leq C_1 C_2(n, p) \|\nabla u\|_{L^p(\mathbb{R}^n)} + |B_1(x)|^{-\frac{1}{p}} \|u\|_{L^p(\mathbb{R}^n)} \\ &\leq C_3 \|u\|_{W^{1,p}(\mathbb{R}^n)}, \end{aligned}$$

where  $C_3$  only depends on  $p$  and  $n$ . Hence,

$$(6.15) \quad \|u\|_{C^0(\mathbb{R}^n)} = \sup_{x \in \mathbb{R}^n} |u(x)| \leq C_3 \|u\|_{W^{1,p}(\mathbb{R}^n)}$$

iv) Let  $x, y \in \mathbb{R}^n$  with  $r := |x - y| > 0$ . Defining  $W := B_r(x) \cap B_r(y)$ , we get

$$\begin{aligned}
|u(x) - u(y)| &= \frac{1}{|W|} \int_W |u(x) - u(y)| dz \leq \frac{1}{|W|} \left( \int_W |u(x) - u(z)| dz + \int_W |u(y) - u(z)| dz \right) \\
&\leq \frac{1}{|B_{\frac{r}{2}}(\frac{x+y}{2})|} \left( \int_{B_r(x)} |u(x) - u(z)| dz + \int_{B_r(y)} |u(y) - u(z)| dz \right) \\
&\leq 2^n \left( \frac{1}{|B_r(x)|} \int_{B_r(x)} |u(x) - u(z)| dz + \frac{1}{|B_r(y)|} \int_{B_r(y)} |u(y) - u(z)| dz \right) \\
&\leq 2^n C_1 \left[ \left( \int_{B_r(x)} |\nabla u(z)|^p dz \right)^{\frac{1}{p}} \left( \int_{B_r(x)} |x - z|^{-(n-1)\frac{p}{p-1}} dz \right)^{\frac{p-1}{p}} \right. \\
&\quad \left. + \left( \int_{B_r(y)} |\nabla u(z)|^p dz \right)^{\frac{1}{p}} \left( \int_{B_r(y)} |y - z|^{-(n-1)\frac{p}{p-1}} dz \right)^{\frac{p-1}{p}} \right] \\
&\leq 2 \cdot 2^n C_1 \|\nabla u\|_{L^p(\mathbb{R}^n)} \left( \omega_n \int_0^r s^{-\frac{(n-1)p}{p-1}} s^{n-1} ds \right)^{\frac{p-1}{p}} \\
&\leq C_4 \left( r^{n-\frac{(n-1)p}{p-1}} \right)^{\frac{p-1}{p}} \|\nabla u\|_{L^p(\mathbb{R}^n)} = C_4 r^{1-\frac{n}{p}} \|\nabla u\|_{L^p(\mathbb{R}^n)}
\end{aligned}$$

with  $C_4 > 0$  only depending on  $n$  and  $p$ . Hence,

$$[u]_{C^{0,\gamma}(\mathbb{R}^n)} = [u]_{C^{0,1-\frac{n}{p}}(\mathbb{R}^n)} = \sup_{x,y \in \mathbb{R}^n, x \neq y} \frac{|u(x) - u(y)|}{|x - y|^{1-\frac{n}{p}}} \leq C_4 \|\nabla u\|_{L^p(\mathbb{R}^n)}.$$

Combining this estimate with (6.15), we obtain (6.13) for  $p \in (n, \infty)$ .  $\square$

We define a version of a function.

**Definition 6.13.** We say that  $u^*: U \rightarrow \mathbb{R}$  is a *version* of the given function  $u: U \rightarrow \mathbb{R}$  if  $u = u^*$  a.e. in  $U$ .

We next summarize embeddings of  $W^{1,p}(\Omega)$  into  $C^{0,\gamma}(\overline{\Omega})$  for various  $p$  and  $\Omega$ .

**Theorem 6.14** (Embeddings of  $W^{1,p}(\Omega)$  for  $p \in (n, \infty]$ ). *Let  $\Omega$  be a bounded domain,  $p \in (n, \infty]$  and  $\gamma = 1 - \frac{n}{p} \in (0, 1]$ .*

a)  $W^{1,p}(\mathbb{R}^n)$  is continuously embedded into  $C^{0,\gamma}(\mathbb{R}^n)$  in the sense that for any  $u \in W^{1,p}(\mathbb{R}^n)$  there is a version  $u^* \in C^{0,\gamma}(\mathbb{R}^n)$  and

$$\|u^*\|_{C^{0,\gamma}(\mathbb{R}^n)} \leq C \|u\|_{W^{1,p}(\mathbb{R}^n)},$$

where  $C > 0$  only depends on  $p$  and  $u$ .

b) If  $\partial\Omega \in C^1$ , then  $W^{1,p}(\Omega)$  is continuously embedded into  $C^{0,\gamma}(\overline{\Omega})$  in the sense that for any  $u \in W^{1,p}(\Omega)$ , there is a version  $u^* \in C^{0,\gamma}(\overline{\Omega})$  and

$$\|u^*\|_{C^{0,\gamma}(\overline{\Omega})} \leq C \|u\|_{W^{1,p}(\Omega)},$$

where  $C > 0$  depends on  $p$ ,  $n$ , and  $\Omega$ .

c)  $W_0^{1,p}(\Omega)$  is continuously embedded into  $C^{0,\gamma}(\overline{\Omega})$  in the sense that for any  $u \in W_0^{1,p}(\Omega)$  there is a version  $u^* \in C^{0,\gamma}(\overline{\Omega})$  and

$$\|u^*\|_{C^{0,\gamma}(\overline{\Omega})} \leq C \|\nabla u\|_{L^p(\Omega)},$$

where  $C > 0$  depends on  $p$ ,  $n$ , and  $\Omega$ .

*Remark 6.15.* In view of Theorem 6.14 b), for any bounded domain  $\Omega \subset \mathbb{R}^n$  with  $\partial\Omega \in C^1$  we may define the trace  $\text{Tr}: W^{1,\infty}(\Omega) \rightarrow C^0(\partial\Omega)$ ,  $\text{Tr}(u) := u^*|_{\partial\Omega}$  which particularly shows that any  $u \in W_0^{1,\infty}(\Omega)$  satisfies  $\text{Tr}(u) = 0$ . However,  $u(x) := 1 - |x| \in W^{1,\infty}(B_1(0))$  with  $u = 0$  on  $\partial B_1(0)$ . (Hence,  $\text{Tr}(u) = 0$ , but  $u \notin W_0^{1,\infty}(B_1(0))$ , as  $\|\nabla u - \nabla \varphi\|_{L^\infty(B_1(0))} \geq 0$  for all  $\varphi \in C_0^\infty(B_1(0))$ .)

*Proof of Theorem 6.14.* i) a) for  $p \in (n, \infty)$ : For  $u \in W^{1,p}(\mathbb{R}^n)$  there is  $(u_m)_{m \in \mathbb{N}} \subset C^1(\mathbb{R}^n) \cap W^{1,p}(\mathbb{R}^n)$  such that  $u_m \rightarrow u$  in  $W^{1,p}(\mathbb{R}^n)$ . By (6.13),  $(u_m)_{m \in \mathbb{N}}$  is a Cauchy sequence in  $C^{0,\gamma}(\mathbb{R}^n)$  and hence there is  $u^* \in C^{0,\gamma}(\mathbb{R}^n)$  such that  $u_m \rightarrow u^*$  in  $C^{0,\gamma}(\mathbb{R}^n)$ . As  $u_{m_l} \rightarrow u$  a.e. in  $\mathbb{R}^n$  as  $l \rightarrow \infty$  for a subsequence, we have  $u = u^*$  a.e. in  $\mathbb{R}^n$  and

$$\|u^*\|_{C^{0,\gamma}(\mathbb{R}^n)} = \lim_{m \rightarrow \infty} \|u_m\|_{C^{0,\gamma}(\mathbb{R}^n)} \stackrel{(6.13)}{\leq} C_1 \lim_{m \rightarrow \infty} \|u_m\|_{W^{1,p}(\mathbb{R}^n)} = C_1 \|u\|_{W^{1,p}(\mathbb{R}^n)}.$$

ii) b) for  $p \in (n, \infty)$ : For  $u \in W^{1,p}(\Omega)$  there is  $E(u) \in W^{1,p}(\mathbb{R}^n)$  by Theorem 5.5 which satisfies  $(E(u))^*|_\Omega = u$  a.e. in  $\Omega$  so that  $(E(u))^*|_\Omega =: u^*$  is a version of  $u$  satisfying

$$\|u^*\|_{C^{0,\gamma}(\bar{\Omega})} \leq \|(E(u))^*\|_{C^{0,\gamma}(\mathbb{R}^n)} \stackrel{i)}{\leq} C_1 \|E(u)\|_{W^{1,p}(\mathbb{R}^n)} \stackrel{\text{Thm. 5.5}}{\leq} C_3 \|u\|_{W^{1,p}(\Omega)},$$

where  $C_3 > 0$  is the constant from Theorem 5.5 depending on  $p, n, \Omega$ .

iii) b) for  $p = \infty$ : Let  $u \in W^{1,\infty}(\Omega)$ . Then  $u \in W^{1,\tilde{p}}(\Omega)$  for some  $\tilde{p} \in (n, \infty)$  as  $\Omega$  is bounded and by ii) there is a version  $u^*$  of  $u$  with  $u^* \in C^{0,\tilde{\gamma}}(\bar{\Omega})$ , where  $\tilde{\gamma} := 1 - \frac{n}{\tilde{p}} \in (0, 1)$ . We fix  $x, y \in \Omega$  with  $x \neq y$ . As  $\partial\Omega \in C^1$  there is a domain  $V \Subset \Omega$  with  $\partial V \in C^1$  and  $x, y \in V$ . By Theorem 4.1  $u_\varepsilon := \eta_\varepsilon * u \in C^\infty(\Omega)$  converge to  $u^*$  in  $W^{1,\tilde{p}}(V)$ , hence by ii)  $u_\varepsilon \rightarrow u^*$  in  $C^{0,\tilde{\gamma}}(\bar{V})$  so that  $u_\varepsilon \rightarrow u^*$  uniformly on  $\bar{V}$  as  $\varepsilon \downarrow 0$ . Furthermore, for  $\varepsilon > 0$  small enough such that  $V \subset \Omega_{\varepsilon,m}$  we have by Theorem 4.1

$$|\nabla u_\varepsilon(z)| = \left| \int_\Omega \eta_\varepsilon(z - \tilde{y}) \nabla u(\tilde{y}) d\tilde{y} \right| \leq \|\nabla u\|_{L^\infty(\Omega)} \underbrace{\int_{\mathbb{R}^n} \eta_\varepsilon(z - \tilde{y}) d\tilde{y}}_{=1} = \|\nabla u\|_{L^\infty(\Omega)}.$$

Hence, the mean value theorem implies for  $\Omega$  convex, as we may choose  $V$  to be convex,

$$|u^*(x) - u^*(y)| = \lim_{\varepsilon \downarrow 0} |u_\varepsilon(x) - u_\varepsilon(y)| \leq \limsup_{\varepsilon \downarrow 0} \|\nabla u_\varepsilon\|_{L^\infty(V)} |x - y| \leq \|\nabla u\|_{L^\infty(\Omega)} |x - y|.$$

Hence, for  $\Omega$  convex, we have

$$\|u^*\|_{C^{0,1}(\bar{\Omega})} = \|u^*\|_{C^0(\bar{\Omega})} + [u^*]_{C^{0,1}(\bar{\Omega})} \leq \|u\|_{L^\infty(\Omega)} + \|\nabla u\|_{L^\infty(\Omega)} \leq \|u\|_{W^{1,\infty}(\Omega)}$$

iv) a) for  $p = \infty$ : Let  $u \in W^{1,\infty}(\mathbb{R}^n)$  and  $\Omega_m := B_m(0)$ ,  $m \in \mathbb{N}$ . Then  $u \in W^{1,\infty}(\Omega_m)$  for any  $m \in \mathbb{N}$  so that iii) implies the existence of a version  $u^*$  of  $u$  such that

$$\|u^*\|_{C^{0,1}(\bar{\Omega}_m)} \leq \|u\|_{W^{1,\infty}(\Omega_m)} \leq \|u\|_{W^{1,\infty}(\mathbb{R}^n)} \quad \text{for all } m \in \mathbb{N}.$$

As  $\|u^*\|_{C^{0,1}(\mathbb{R}^n)} = \sup_{m \in \mathbb{N}} \|u^*\|_{C^{0,1}(\bar{\Omega}_m)}$ , the claim is proved.

v) c) for  $p \in (n, \infty]$ : For  $u \in W_0^{1,p}(\Omega)$  there is  $(u_m)_{m \in \mathbb{N}} \subset C_0^\infty(\Omega)$  with  $u_m \rightarrow u$  in  $W^{1,p}(\Omega)$ . Extending  $u_m$  by 0 on  $\mathbb{R}^n \setminus \Omega$ , we have  $u_m \in C_0^\infty(\mathbb{R}^n)$  and by a) there is  $v \in C^{0,\gamma}(\mathbb{R}^n) \cap$

$W^{1,p}(\mathbb{R}^n)$  such that  $u_m \rightarrow v$  in  $C^{0,\gamma}(\mathbb{R}^n)$  and in  $W^{1,p}(\mathbb{R}^n)$ . As  $v = 0$  in  $\mathbb{R}^n \setminus \Omega$  we conclude with  $u^* := v|_{\bar{\Omega}}$  and Poincaré's inequality (Corollary 6.7)

$$\|u^*\|_{C^{0,\gamma}(\bar{\Omega})} = \|v\|_{C^{0,\gamma}(\mathbb{R}^n)} \stackrel{\text{a)}}{\leq} \tilde{C}_4 \|v\|_{W^{1,p}(\mathbb{R}^n)} = \tilde{C}_4 \|u\|_{W^{1,p}(\Omega)} \stackrel{\text{Poincaré}}{\leq} C_4 \|\nabla u\|_{L^p(\Omega)}$$

as  $u = v$  a.e. in  $\Omega$ .

vi) *End of part iii) for  $\Omega$  non-convex:* With the notation from Definition 5.6 and  $\Phi_i, \Psi_i$  from Lemma 5.3 (with  $\gamma = \gamma_i$ ),  $i = 1, \dots, N$ , we may choose  $U_i$  small enough such that

$$\Phi_i(\Omega \cap U_i) \subset B_i^+ \subset \Phi_i(\Omega) \quad \text{for all } i \in \{1, \dots, N\}$$

and some balls  $B_i := B_{s_i}(x^i)$ . As  $\bar{\Omega}$  is compact, there is  $\delta > 0$  such that for  $x, y \in \Omega$  with  $|x - y| < \delta$ , either  $x, y \in \overline{B_\delta(x)} \subset \Omega$  or  $x, y \in \Omega \cap U_i$  for some  $i \in \{1, \dots, N\}$ . Then for  $x, y \in \Omega$  we distinguish three cases:

I)  $|x - y| < \delta$  and  $x, y \in \overline{B_\delta(x)}$ : Then we may choose (in iii))  $V = B_\delta(x)$ . As  $V$  is convex, the mean value theorem implies

$$|u_\varepsilon(x) - u_\varepsilon(y)| \leq \|\nabla u_\varepsilon\|_{L^\infty(V)} |x - y| \leq \|\nabla u\|_{L^\infty(\Omega)} |x - y|$$

as in iii).

II)  $|x - y| < \delta$  and  $x, y \in \Omega \cap U_i$ : We define the convex hull

$$W := \{(1 - t) \Phi_i(x) + t \Phi_i(y) : t \in [0, 1]\} \subset B_i^+$$

and we may choose  $V$  in iii) such that  $\Phi_i^{-1}(W) \subset V$ . Then

$$\begin{aligned} |u_\varepsilon(x) - u_\varepsilon(y)| &= |u_\varepsilon(\Psi_i(\Phi_i(x))) - u_\varepsilon(\Psi_i(\Phi_i(y)))| \\ &= \left| \int_0^1 \frac{d}{dt} (u_\varepsilon \circ \Psi_i)((1 - t)\Phi_i(x) + t\Phi_i(y)) dt \right| \\ &\leq \|\nabla(u_\varepsilon \circ \Psi_i)\|_{L^\infty(W)} \cdot |\Phi_i(x) - \Phi_i(y)| \\ &\leq \|\nabla u_\varepsilon\|_{L^\infty(V)} \cdot \|D\Psi_i\|_{L^\infty(W)} \cdot \|\Phi_i\|_{L^\infty(\bar{B})} \cdot |x - y|, \end{aligned}$$

where we used the chain rule and chose a ball  $\bar{B}$  such that  $\bar{\Omega} \Subset B$  which by iii) yields

$$\leq \tilde{C}_3 \|\nabla u\|_{L^\infty(\Omega)} |x - y|,$$

where  $\tilde{C}_3 := \max_{1 \leq i \leq N} \|D\Psi_i\|_{L^\infty(\Phi_i(\Omega))} \cdot \|D\Phi_i\|_{L^\infty(\bar{B})}$ .

III)  $|x - y| \geq \delta$ : Then  $|u^*(x) - u^*(y)| \leq 2 \|u^*\|_{C^0(\bar{\Omega})} \cdot \frac{1}{\delta} |x - y|$ .

Altogether, letting  $\varepsilon \downarrow 0$ , we have

$$\|u^*\|_{C^{0,1}(\bar{\Omega})} \leq \|u\|_{L^\infty(\Omega)} + \left( \frac{2}{\delta} \|u\|_{L^\infty(\Omega)} + (1 + \tilde{C}_3) \|\nabla u\|_{L^\infty(\Omega)} \right) \leq C_3 \|u\|_{W^{1,\infty}(\Omega)}. \quad \square$$

### 6.3 General Embeddings and Sobolev Inequalities

Using the estimates from Section 6.1 and Section 6.2, we get more complicated estimates and embeddings for  $W^{k,p}(\Omega)$  with  $k \in \mathbb{N}$ . We set

$$W^{0,q} := L^q(\Omega)$$

and let

$$[x] := \max\{z \in \mathbb{Z} : z \leq x\}$$

for  $x \in \mathbb{R}$  denote the *floor function*.

**Theorem 6.16** (Embeddings for  $W^{k,p}(\Omega)$ ). *Let  $\Omega \subset \mathbb{R}^n$  be a bounded domain with  $\partial\Omega \in C^1$ ,  $p, q \in [1, \infty]$ , and  $k \in \mathbb{N}, l \in \mathbb{N}_0$  with  $k \geq l$ .*

a) *If  $k - \frac{n}{p} < l$  and  $k - \frac{n}{p} \geq l - \frac{n}{q}$ , then  $W^{k,p}(\Omega)$  is continuously embedded into  $W^{l,q}(\Omega)$  and there is  $C > 0$  depending only on  $p, q, k, l, n$ , and  $\Omega$  such that*

$$\|u\|_{W^{l,q}(\Omega)} \leq C \|u\|_{W^{k,p}(\Omega)} \quad \text{for all } u \in W^{k,p}(\Omega).$$

b) *If  $k - \frac{n}{p} = l$  and  $q \in [1, \infty)$  (i.e.  $k - \frac{n}{p} > l - \frac{n}{q}$ ), then  $W^{k,p}(\Omega)$  is continuously embedded into  $W^{l,q}(\Omega)$  and there is  $C > 0$  depending on  $p, q, k, l, n$ , and  $\Omega$  such that*

$$\|u\|_{W^{l,q}(\Omega)} \leq C \|u\|_{W^{k,p}(\Omega)} \quad \text{for all } u \in W^{k,p}(\Omega).$$

c) *If  $l < k - \frac{n}{p} \leq l + 1$  (i.e.  $l = k - \left[\frac{n}{p}\right] - 1$ ) and, setting  $\frac{n}{p} = 1$  if  $p = \infty$ ,*

$$\gamma = \begin{cases} \left[\frac{n}{p}\right] + 1 - \frac{n}{p}, & \text{if } \frac{n}{p} \notin \mathbb{N}, \\ \text{arbitrary in } (0, 1), & \text{if } \frac{n}{p} \in \mathbb{N}, \end{cases}$$

*then  $W^{k,p}(\Omega)$  is continuously embedded into  $C^{l,\gamma}(\overline{\Omega})$  and there is  $C > 0$  depending on  $p, \gamma, k, l, n$ , and  $\Omega$  such that*

$$\|u\|_{C^{l,\gamma}(\overline{\Omega})} \leq C \|u\|_{W^{k,p}(\Omega)}.$$

*This embedding is to be understood up to the choice of a continuous version.*

*Proof.* i) If  $u \in W^{m,r}(\Omega)$  with some  $m \in \mathbb{N}$  and  $r \in [1, n)$ , then  $D^\alpha u \in W^{1,r}(\Omega)$  for all  $|\alpha| \leq m - 1$  by Proposition 3.8 and by Theorem 6.5  $D^\alpha u \in L^q(\Omega)$  for all  $q \in [1, r^*]$  and hence  $u \in W^{m-1,q}(\Omega)$  with

$$\|u\|_{W^{m-1,q}(\Omega)} \leq C_1 \sum_{|\alpha| \leq m-1} \|D^\alpha u\|_{L^q(\Omega)} \leq C_2 \sum_{|\alpha| \leq m-1} \|D^\alpha u\|_{W^{1,r}} \leq C_3 \|u\|_{W^{m,r}(\Omega)}$$

with  $C_3$  depending on  $n, r, q, m$ , and  $\Omega$ . Hence, defining  $p_0 := p$  and  $p_j := p_{j-1}^*$  for  $j = 1, \dots, k - l$ , we see that  $\frac{1}{p_j} = \frac{1}{p_{j-1}} - \frac{1}{n}$  and therefore  $\frac{1}{p_j} = \frac{1}{p} - \frac{j}{n}$ ,  $p_j = \frac{np}{n-jp}$  with  $p_j > p_{j-1}$ . If  $p_j < n$  (i.e.  $\frac{n}{p} > j + 1$ ) we have  $p_i < n$  for all  $i \in \{0, \dots, j\}$  and the previous argument yields the continuous embeddings of  $W^{k-(i-1),p_{i-1}}(\Omega)$  into  $W^{k-i,p_i}(\Omega)$  for all  $i \in \{1, \dots, j+1\}$  and  $\tilde{C}_i > 0$  depending on  $h, i, p, n, \Omega$  such that

$$\|u\|_{W^{k-i,p_i}(\Omega)} \leq \tilde{C}_i \|u\|_{W^{k-(i-1),p_{i-1}}(\Omega)} \quad \text{for all } u \in W^{k-(i-1),p_{i-1}}(\Omega).$$

Hence, by combining these estimates for  $i = 1, \dots, j+1$  we have

$$(6.16) \quad \|u\|_{W^{k-(j+1), p_{j+1}}(\Omega)} \leq \tilde{C}_1 \cdot \tilde{C}_2 \cdot \dots \cdot \tilde{C}_{j+1} \|u\|_{W^{k,p}(\Omega)} \quad \text{for all } u \in W^{k,p}(\Omega)$$

if  $\frac{n}{p} > j+1$ .

ii) *Proof of a*): As  $k - \frac{n}{p} < l$  implies  $\frac{n}{p} > k - l$ , we apply (6.16) with  $j := k - l - 1$  and obtain

$$\|u\|_{W^{l, p_{n-l}}(\Omega)} \leq C_4 \|u\|_{W^{k,p}(\Omega)}.$$

As  $\frac{1}{p_{n-l}} = \frac{1}{p} - \frac{k-l}{n}$  implies  $k - \frac{n}{p} = l - \frac{n}{p_{k-l}}$  and hence  $q \leq p_{n-l}$ , Hölders inequality and the boundedness of  $\Omega$  imply that  $W^{l, p_{k-l}}(\Omega)$  is proved ( $\|u\|_{W^{l,q}(\Omega)} \leq C_5 \|u\|_{W^{l, p_{k-l}}(\Omega)}$ )

□

## Chapter 7

# Applications to PDEs



# Bibliography

- [AF03] Robert A. Adams and John J. F. Fournier. *Sobolev spaces*, volume 140 of *Pure and applied mathematics*. Academic press, New York, 2. edition, 2003.
- [Alt12] Hans Wilhelm Alt. *Lineare Funktionalanalysis : eine anwendungsorientierte Einführung*. Springer-Verlag, Berlin, 6. edition, 2012.
- [Bre11] Haim Brezis. *Functional analysis, Sobolev spaces and partial differential equations*. Universitext. Springer-Verlag, New York, 1. edition, 2011.
- [Dob10] Manfred Dobrowolski. *Angewandte Funktionalanalysis : Funktionalanalysis, Sobolev-Räume und elliptische Differentialgleichungen*. Springer-Verlag, Berlin, 2. edition, 2010.
- [Eva10] Lawrence C. Evans. *Partial differential equations*, volume 19 of *Graduate studies in mathematics*. American Mathematical Society, Providence, 2. edition, 2010.
- [MS64] Norman G. Meyers and James Serrin. H = W. *Proceedings of the National Academy of Sciences*, 51(1):1055–1056, 1964.