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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 $f \in \mathrm{C}^0(\overline{\Omega})$ be given. We look for a solution $u \in \mathrm{C}^2(\overline{\Omega})$ to the Poisson equation in one dimension,

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

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 $\varphi \in \mathrm{C}_0^\infty(\Omega)$ (infinitely often differentiable with compact support in Ω). Then integration by parts shows

$$\int_0^1 -u''(x)\varphi(x)\,\mathrm{d}x = -u'(1)\varphi(1) + u'(0)\varphi(0) + \int_0^1 u'(x)\varphi'(x)\,\mathrm{d}x.$$

Hence, in view of (1.1)

$$\int_\Omega u'(x)\varphi'(x)\,\mathrm{d}x = \int_\Omega f(x)\varphi(x)\,\mathrm{d}x \quad \text{for all } \varphi \in \mathrm{C}_0^\infty(\Omega). \tag{1.2}$$

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. □

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 $u \in \mathrm{C}^1(\Omega)$. Then for $i \in \{1, \ldots, n\}$ we have*

$$\int_\Omega \frac{\partial u}{\partial x_i} \varphi \, \mathrm{d}x = -\int_\Omega u \frac{\partial \varphi}{\partial x_i} \, \mathrm{d}x \quad \textit{for all } \varphi \in \mathrm{C}_0^\infty(\Omega). \tag{1.3}$$

Proof. As in general neither $\partial\Omega$ nor the boundary of the support of φ 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 $w \in \mathrm{C}^1(\Omega)$ and $w = 0$ in a neighborhood of $\partial\Omega$, we conclude that $w \in \mathrm{C}^1(\mathbb{R}^n)$. Take an open ball B large enough such that it contains the support of φ. Then by Gauß' (or Green's formula) we have

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

where ν is the outward unit normal on ∂B. Hence, the product rule implies (1.3). □

(1.3) makes sense even if $u, \frac{\partial u}{\partial x_i} \in \mathrm{L}^1_{\mathrm{loc}}(\Omega)$ (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, $u \in \mathrm{L}^1_{\mathrm{loc}}(\Omega)$ and $i \in \{1, \ldots, n\}$. u has the *weak partial derivative* $\frac{\partial u}{\partial x_i}$, if there is $v \in \mathrm{L}^1_{\mathrm{loc}}(\Omega)$ such that

$$\int_\Omega u(x) \frac{\partial u}{\partial x_i}(x) \, \mathrm{d}x = -\int_\Omega v(x)\varphi(x) \, \mathrm{d}x \quad \text{for all } \varphi \in \mathrm{C}_0^\infty(\Omega). \tag{1.4}$$

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 $u \in \mathrm{C}^1(\Omega)$, 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 $u \in \mathrm{C}^1(\overline{\Omega} \setminus \{0\}) \cap \mathrm{C}^0(\overline{\Omega})$, we may use the fundamental theorem of calculus to obtain for $\varphi \in \mathrm{C}_0^\infty(\Omega)$:

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

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

Then $v \in \mathrm{L}^1(\Omega)$ 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 $v \in \mathrm{L}^1_{\mathrm{loc}}(\Omega)$ and for all $\varphi \in \mathrm{C}_0^\infty(\Omega)$ we have

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

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

$$-2\varphi(0) = -\int_\Omega w(x)\varphi(x)\,\mathrm{d}x \quad \text{for all } \varphi \in \mathrm{C}_0^\infty(\Omega). \tag{1.5}$$

Fix some $f \in \mathrm{C}_0^\infty((-1,1))$ 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 $\varphi_n \in \mathrm{C}_0^\infty((-1,1))$ with $\varphi_n(x) = 0$ for all $x \in \mathbb{R}\setminus\left(-\frac{1}{n}, \frac{1}{n}\right)$ with $\varphi_n(0) = 1$ and $\lim_{n\to\infty}\varphi_n(x) = 0$ for all $x \in \Omega \setminus \{0\}$. As $\|\varphi_n\|_{\mathrm{L}^\infty(\Omega)} \le \|f\|_{\mathrm{L}^\infty(\Omega)} < \infty$ we conclude from the dominated convergence theorem that

$$0 = \lim_{n\to\infty}\left(-\int_\Omega w(x)\varphi_n(x)\,\mathrm{d}x\right) \neq -2 = \lim_{n\to\infty} -2\varphi_n(x)$$

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

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

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

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 $f \in \mathrm{L}^2(\Omega)$. Then in view of (1.2) we say that u is a *weak solution* to (1.1) if $u \in \mathrm{W}^{1,2}(\Omega)$,

$$\int_\Omega u'(x)\varphi'(x)\,\mathrm{d}x = \int_\Omega f(x)\varphi(x) \quad \text{for all } \varphi \in \mathrm{C}_0^\infty(\Omega),$$

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 **??**, as $u \in \mathrm{W}^{1,2}(\Omega)$ is not necessarily continuous. In Chapter **??**, 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 $\mathrm{L}^p(\Omega)$

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

2.1 $\mathrm{L}^p(\Omega)$: definition and basic properties

i) If $u, v\colon \Omega \to [-\infty, \infty]$ are measurable on Ω, they are equivalent if $u = v$ a.e. in Ω. $[u]$ 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

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

where

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

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

iii) $\mathrm{L}^p(\Omega)$ 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 $p \in [1, \infty]$, $(u_n)_{n\in\mathbb{N}} \subset \mathrm{L}^p(\Omega)$ and $u \in \mathrm{L}^p(\Omega)$, such that $u_n \to u$ in $\mathrm{L}^p(\Omega)$, i.e. $\|u_n - u\|_{\mathrm{L}^p(\Omega)} \to 0$ as $n \to \infty$. Then there is a subsequence $(u_{n_k})_{k\in\mathbb{N}}$ and a function $h \in \mathrm{L}^p(\Omega)$ such that $u_{n_k}(x) \to u(x)$ a.e. in Ω as $k \to \infty$ and $|u_{n_k}(x)| \le h(x)$ a.e. in Ω for all $k \in \mathbb{N}$.

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

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

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

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

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

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

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

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

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

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

2.2 Limit theorems and Fubini

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

$$\int_\Omega \left(\lim_{n \to \infty} u_n(x) \right) \mathrm{d}x = \lim_{n \to \infty} \int_\Omega u_n(x) \, \mathrm{d}x.$$

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

$$\int_\Omega \left(\liminf_{n \to \infty} u_n(x) \right) \mathrm{d}x \leq \liminf_{n \to \infty} \int_\Omega u_n(x) \, \mathrm{d}x.$$

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

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:

$$I_1 = \int_{\mathbb{R}^{n+m}} |u(x, y)| \, \mathrm{d}x \, \mathrm{d}y,$$
$$I_2 = \int_{\mathbb{R}^m} \left(\int_{\mathbb{R}^n} |u(x, y)| \, \mathrm{d}x \right) \mathrm{d}y,$$
$$I_2 = \int_{\mathbb{R}^n} \left(\int_{\mathbb{R}^m} |u(x, y)| \, \mathrm{d}y \right) \mathrm{d}x.$$

Then $u(\cdot, y) \in \mathrm{L}^1(\mathbb{R}^n)$ for a.e. $y \in \mathbb{R}^m$, $\int_{\mathbb{R}^m} u(\cdot, y) \, \mathrm{d}y \in \mathrm{L}^1(\mathbb{R}^n)$, $u(x, \cdot) \in \mathrm{L}^1(\mathbb{R}^m)$ for a.e. $x \in \mathbb{R}^n$, $\int_{\mathbb{R}^n} u(x, \cdot) \, \mathrm{d}x \in \mathrm{L}^1(\mathbb{R}^m)$ 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) $\mathrm{C}_0^\infty(\Omega)$ is dense in $\mathrm{L}^p(\Omega)$ for any $p \in [1, \infty)$, i.e. for any $u \in \mathrm{L}^p(\Omega)$ and $\varepsilon > 0$ there is $\varphi \in \mathrm{C}_0^\infty(\Omega)$ such that $\|\varphi - u\|_{\mathrm{L}^p(\Omega)} < \varepsilon$.

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

$$\begin{aligned} \mathrm{B}_\varepsilon(x) &\coloneqq \{y \in \mathbb{R}^n \colon |y - x| < \varepsilon\}, \\ \Omega_\varepsilon &\coloneqq \{x \in \Omega \colon \operatorname{dist}(x, \partial\Omega) > \varepsilon\}, \qquad \text{and} \\ \mathrm{L}^p_{\mathrm{loc}}(\Omega) &\coloneqq \{u \colon \Omega \to [-\infty, \infty] \colon u \in \mathrm{L}^p(V) \text{ for all } V \Subset \Omega\}, \quad \text{for } p \in [1, \infty]. \end{aligned}$$

iii) Standard mollifier: Let

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

where $c > 0$ is chosen such that $\int_{\mathbb{R}^n} \eta(x)\,\mathrm{d}x = 1$. Then $\eta \in \mathrm{C}_0^\infty(\mathbb{R}^n)$ is called *standard mollifier.* For $\varepsilon > 0$, $\eta_\varepsilon(x) \coloneqq \frac{1}{\varepsilon^n}\eta\left(\frac{x}{\varepsilon}\right), x \in \mathbb{R}^n$, satisfies $\eta_\varepsilon \in \mathrm{C}_0^\infty(\mathbb{R}^n)$, $\int_{\mathbb{R}^n} \eta_\varepsilon(x)\,\mathrm{d}x = 1$, and $\operatorname{supp}(\eta_\varepsilon) = \overline{\mathrm{B}_\varepsilon(0)}$.

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

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

The mollification has the following properties:

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

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

b) If $\operatorname{supp}(u) \Subset \Omega$, then $u_\varepsilon \in \mathrm{C}_0^\infty(\Omega)$ for small enough ε.

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

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

e) $u \in \mathrm{L}^1_{\mathrm{loc}}(\Omega)$, then $u_\varepsilon \in \mathrm{C}^\infty(\Omega_\varepsilon)$.

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

$$\mathrm{D}_i^h v(x) \coloneqq \frac{1}{h}(v(x + he_i) - v(x)), \quad x \in \mathbb{R}^n.$$

As $\eta_\varepsilon \in \mathrm{C}_0^\infty(\mathbb{R}^n)$ we have $\nabla\eta_\varepsilon \in \mathrm{L}^\infty(\mathbb{R}^n)^n$. So $\mathrm{D}_i^h\eta_\varepsilon \in \mathrm{L}^\infty(\mathbb{R}^n)$ by the mean value theorem. As moreover $\mathrm{D}_i^h\eta_\varepsilon(z) \to \frac{\partial\eta_\varepsilon}{\partial x_i}(z)$ as $h \to 0$ for any $z \in \mathbb{R}^n$, the dominated convergence theorem implies

$$\begin{aligned}\mathrm{D}_i^h(u_\varepsilon)(x) &= \int_\Omega \frac{1}{h}(\eta_\varepsilon(x+he_i-y)-\eta_\varepsilon(x-y))u(y)\,\mathrm{d}y = \int_\Omega(\,\mathrm{D}_i^h\eta_\varepsilon(x-y))u(y)\,\mathrm{d}y\\ &\to \int_\Omega \frac{\partial\eta_\varepsilon}{\partial x_i}(x-y)u(y)\,\mathrm{d}y \quad \text{as } \varepsilon\downarrow 0.\end{aligned}$$

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

$$\lim_{r\downarrow 0}\frac{1}{|\mathrm{B}_r(x)|}\int_{\mathrm{B}_r(x)}|u(y)-u(x)|\,\mathrm{d}y = 0. \tag{2.1}$$

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

$$\begin{aligned}|u_\varepsilon(x)-u(x)| &= |\int_{\mathrm{B}_\varepsilon(x)}\eta_\varepsilon(x-y)f(y)\,\mathrm{d}y| = |\int_{\mathrm{B}_\varepsilon(x)}\eta_\varepsilon(x-y)(f(y)-f(x))\,\mathrm{d}y|\\ &\le \frac{1}{\varepsilon^n}\int_{\mathrm{B}_\varepsilon(x)}\|\eta\|_{\mathrm{L}^\infty(\mathbb{R}^n)}|f(y)-f(x)|\,\mathrm{d}y \le \frac{C}{|\mathrm{B}_\varepsilon(x)|}\int_{\mathrm{B}_\varepsilon(x)}|f(y)-f(x)|\,\mathrm{d}y\\ &\to 0 \quad \text{as } \varepsilon\downarrow 0\end{aligned} \tag{2.2}$$

due to (2.1).

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

$$u_\varepsilon(x) = \int_{\mathrm{B}_\varepsilon(x)\cap\Omega}\eta_\varepsilon(x-y)u(y)\,\mathrm{d}y = 0.$$

Hence, $\operatorname{supp}(u_\varepsilon) \subset \overline{\Omega_{\frac{\delta}{3}}} \Subset \Omega$. By a), $u_\varepsilon \in \mathrm{C}_0^\infty(\Omega)$.

c) For $u \in \mathrm{C}^0(\Omega)$ 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 $u_\varepsilon \to u$ uniformly in V.

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

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

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

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

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

Given $\mu > 0$, we may choose $\varphi \in \mathrm{C}_0^\infty(\Omega)$ such that $\|u - \varphi\|_{\mathrm{L}^p(\Omega)} < \frac{\mu}{3}$. As φ and φ_ε have compact support in Ω by *b*), we deduce from c) that $\varphi_\varepsilon \to \varphi$ uniformly in Ω as $\varepsilon \downarrow 0$. Hence, we may choose $\varepsilon_0 > 0$ small enough such that $\|\varphi_\varepsilon - \varphi\|_{\mathrm{L}^p(\Omega)} < \frac{\mu}{3}$ for all $\varepsilon \in (0, \varepsilon_0)$. But then,

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

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

2.4 Polar coordinates

Let $f \in \mathrm{C}^1(\overline{\mathrm{B}_r(x_0)})$ with $x_0 \in \mathbb{R}^n$, $r > 0$. Then by the transformation rule with $x = x_0 + sz$, $s \in (0, r)$, $z \in \partial\mathrm{B}_1(0)$ we have

$$\int_{\mathrm{B}_r(x_0)} f(x)\,\mathrm{d}x = \int_0^r \left(\int_{\partial\mathrm{B}_s(x_0)} f\,\mathrm{d}\sigma(x) \right) \mathrm{d}s = \int_0^r s^{n-1} \int_{\partial\mathrm{B}_1(0)} f(x_0 + sz)\,\mathrm{d}\sigma(z)\,\mathrm{d}s.$$

In particular, if $x_0 = 0$, f is radially symmetric and ω_n is the surface $|\partial\mathrm{B}_1(0)|$ of $\partial\mathrm{B}_1(0)$, we get

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

where $s = |x|$.

Proof. Appendix in [Eva10]. ☐

Chapter 3

Weak derivatives and definitions of Sobolev spaces

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

$$\int_\Omega u(x)\varphi_{x_i}(x)\,\mathrm{d}x = -\int_\Omega u_{x_i}(x)\varphi(x)\,\mathrm{d}x \quad \text{for all } \varphi \in \mathrm{C}_0^\infty(\Omega). \tag{3.1}$$

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

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

$$\int_\Omega u(x)\,\mathrm{D}^\alpha\varphi(x) = (-1)^{|\alpha|}\int_\Omega \mathrm{D}^\alpha u(x)\varphi(x)\,\mathrm{d}x \quad \textit{for all } \varphi \in \mathrm{C}_0^\infty(\Omega). \tag{3.2}$$

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

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

and (3.2) follows by applying (3.1) k times. □

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

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

$$\int_\Omega u(x)\,\mathrm{D}^\alpha\varphi(x)\,\mathrm{d}x = (-1)^{|\alpha|}\int_\Omega v(x)\varphi(x)\,\mathrm{d}x \quad \text{for all } \varphi \in \mathrm{C}_0^\infty(\Omega). \tag{3.3}$$

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

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 $u \in \mathrm{L}^1_{\mathrm{loc}}(\Omega)$. Then we have the equivalence*

$$\int_\Omega u(x)\varphi(x)\,\mathrm{d}x = 0 \quad \textit{for all } \varphi \in \mathrm{C}_0^\infty(\Omega) \iff u = 0 \textit{ a.e. in } \Omega.$$

Proof. " $\Longleftarrow$ " is obvious.

" $\Longrightarrow$ ": Let $u \in \mathrm{L}^1_{\mathrm{loc}}(\Omega)$ with $\int_\Omega u\varphi \,\mathrm{d}x = 0$ for all $\varphi \in \mathrm{C}_0^\infty(\Omega)$. We fix $K \subset \Omega$ compact and define

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

and

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

As $|u| < \infty$ a.e. in K a.e., we have $u(x)f(x) = |u(x)|$ for a.e. $x \in K$. Since $f \in \mathrm{L}^\infty(\Omega)$ with $\operatorname{supp}(f) \subset K \Subset \Omega$, we define $\varphi_n := f_{\frac{1}{n}} = \eta_{\frac{1}{n}} * f$ and deduce from Theorem 2.1 a), b) that $\varphi_n \in \mathrm{C}_0^\infty(\Omega)$ and $\varphi_{n_k}(x) \to f(x)$ a.e. in Ω as $k \to \infty$ for some subsequence. As moreover

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

the dominated convergence theorem implies

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

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

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

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

$$\int_\Omega (v - \tilde{v})(x)\varphi(x) \,\mathrm{d}x = 0 \quad \text{for all } \varphi \in \mathrm{C}_0^\infty(\Omega).$$

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

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

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

with the norm

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

We further define

$$\mathrm{W}^{k,p}_0(\Omega) := \overline{\mathrm{C}^\infty_0(\Omega)}^{\|\cdot\|_{\mathrm{W}^{k,p}(\Omega)}}$$

to be the closure of $\mathrm{C}^\infty_0(\Omega)$ in $\mathrm{W}^{k,p}(\Omega)$ and

$$\mathrm{W}^{k,p}_{\mathrm{loc}}(\Omega) := \bigcap_{V \Subset \Omega} W^{k,p}(V).$$

For $p = 2$, we define $\mathrm{H}^k(\Omega) := \mathrm{W}^{k,2}(\Omega)$ and $\mathrm{H}^k_0(\Omega) := \mathrm{W}^{k,2}_0(\Omega)$.

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

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

We say $u_m \to u$ in $\mathrm{W}^{k,p}_{\mathrm{loc}}(\Omega)$ if $u_m \to u$ in $\mathrm{W}^{k,p}(V)$ for all $V \Subset \Omega$.

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

b) $u \in \mathrm{W}^{k,p}_0(\Omega)$ if and only if there exists $(u_m)_{m\in\mathbb{N}} \subset \mathrm{C}^\infty_0(\Omega)$ such that $u_m \to u$ in $\mathrm{W}^{k,p}(\Omega)$. We interpret $W^{k,p}_0(\Omega)$ as the set of $u \in W^{k,p}(\Omega)$ such that "$\mathrm{D}^\alpha u = 0$ on $\partial\Omega$ for any $|\alpha| \le k-1$". This interpretation will be made precise in Chapter **??**.

c) The letter "H" in $\mathrm{H}^k(\Omega)$ and $\mathrm{H}^k_0(\Omega)$ is used as those are Hilbert spaces as we will see soon.

Example 3.7. Let $\Omega = \mathrm{B}_1(0) \subset \mathbb{R}^n$, $u(x) = |x|^{-a}$ for $x \in \Omega \setminus \{0\}$ with some $a > 0$. Given $p \in [1,\infty)$, for which a do we have $u \in \mathrm{W}^{1,p}(\Omega)$?
Since $u \in C^\infty(\Omega \setminus \{0\})$, we have for $x \neq 0$

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

For fixed $\varphi \in \mathrm{C}^\infty_0(\Omega)$ and $\varepsilon > 0$, Green's formula (ν is the outward unit normal on $\Omega \setminus \overline{\mathrm{B}_\varepsilon(0)}$) implies

$$\int_{\Omega\setminus\overline{\mathrm{B}_\varepsilon(0)}} u\,\varphi_{x_i}\,\mathrm{d}x = -\int_{\Omega\setminus\overline{\mathrm{B}_\varepsilon(0)}} u_{x_i}\varphi\,\mathrm{d}x + \underbrace{\int_{\partial\Omega} u\,\varphi\,\nu_i\,\mathrm{d}\sigma}_{=0} + \int_{\partial\mathrm{B}_\varepsilon(0)} u\,\varphi\,\nu_i\,\mathrm{d}\sigma. \tag{3.4}$$

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

$$\left|\int_{\partial\mathrm{B}_\varepsilon(0)} u\,\varphi\,\nu_i\,\mathrm{d}\sigma\right| \le \|\varphi\|_{\mathrm{L}^\infty(\Omega)} \int_{\partial\mathrm{B}_\varepsilon(0)} \varepsilon^{-a}\,\mathrm{d}\sigma \le C\varepsilon^{k-1-a} \to 0 \text{ as } \varepsilon \downarrow 0.$$

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

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

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

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

a) $\mathrm{D}^\alpha u \in W^{k-|\alpha|,p}(\Omega)$ *(with $\mathrm{W}^{0,p}(\Omega) = \mathrm{L}^p(\Omega)$) and $\mathrm{D}^\beta(\mathrm{D}^\alpha(u)) = \mathrm{D}^\alpha(\mathrm{D}^\beta(u)) = \mathrm{D}^{\alpha+\beta}(u)$ for all $\alpha, \beta \in \mathbb{N}_0^n$ with $|\alpha| + |\beta| \le k$.*

b) For $\lambda, \mu \in \mathbb{R}$ we have $\lambda u + \mu v \in \mathrm{W}^{k,p}(\Omega)$ and $\mathrm{D}^\alpha(\lambda u + \mu v) = \lambda\,\mathrm{D}^\alpha u + \mu\,\mathrm{D}^\alpha v$.

c) If $V \subset \Omega$ is open, then $u \in \mathrm{W}^{k,p}(V)$.

d) If $\xi \in \mathrm{C}_0^\infty(\Omega)$, then $\xi u \in \mathrm{W}^{k,p}(\Omega)$ and Leibniz's formula

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

holds with

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

and

$$\beta \le \alpha \iff \forall i \in \{1,\ldots,n\}\colon \beta_i \le \alpha_i.$$

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

a) Let $\varphi \in \mathrm{C}_0^\infty(\Omega)$. Then $\mathrm{D}^\beta\varphi \in \mathrm{C}_0^\infty(\Omega)$ and (3.3) implies

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

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

d) Let $\varphi \in \mathrm{C}_0^\infty(\Omega)$. In case of $|\alpha| = 1$, we have

$$\int_\Omega \xi u\,\mathrm{D}^\alpha\varphi\,\mathrm{d}x = \int_\Omega \left(u\,\mathrm{D}^\alpha(\xi\varphi) - u(\mathrm{D}^\alpha\xi)\varphi\right)\,\mathrm{d}x \overset{(3.3)}{=} -\int_\Omega \left(\xi\,\mathrm{D}^\alpha u + u\,\mathrm{D}^\alpha\xi\right)\varphi\,\mathrm{d}x.$$

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

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

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

$$\begin{aligned}
\int_\Omega \xi u \, \mathrm{D}^\alpha \varphi &= \int_\Omega \xi u \, \mathrm{D}^\beta (\, \mathrm{D}^\gamma \varphi) \, \mathrm{d}x \\
&\overset{\text{(IA)}}{=} (-1)^{|\beta|} \int_\Omega \sum_{\sigma \le \beta} \binom{\beta}{\sigma} \mathrm{D}^\sigma \xi \; \mathrm{D}^{\beta-\sigma} u \; \mathrm{D}^\gamma \varphi \, \mathrm{d}x \\
&\overset{(3.3)}{=} (-1)^{|\beta|+|\gamma|} \int_\Omega \sum_{\sigma \le \beta} \binom{\beta}{\sigma} \mathrm{D}^\gamma \left(\mathrm{D}^\sigma \xi \; \mathrm{D}^{\beta-\sigma} u \right) \varphi \, \mathrm{d}x \\
&\overset{\text{(IA)}}{=} (-1)^{|\alpha|} \int_\Omega \sum_{\sigma \le \beta} \binom{\beta}{\sigma} \left[\mathrm{D}^{\sigma+\gamma} \xi \; \mathrm{D}^{\beta-\sigma} u + \mathrm{D}^\sigma \xi \; \mathrm{D}^{\alpha-\sigma} u \right] \varphi \, \mathrm{d}x \\
&= (-1)^{|\alpha|} \int_\Omega \sum_{\sigma \le \beta} \binom{\beta}{\sigma} \left[\mathrm{D}^{\sigma+\gamma} \xi \; \mathrm{D}^{\alpha-(\sigma+\gamma)} u + \mathrm{D}^\sigma \xi \; \mathrm{D}^{\alpha-\sigma} u \right] \varphi \, \mathrm{d}x \\
&= (-1)^{|\alpha|} \int_\Omega \left[\sum_{\gamma \le \rho \le \alpha} \binom{\beta}{\rho-\gamma} + \sum_{0 \le \rho \le \beta} \binom{\beta}{\rho} \right] \mathrm{D}^\rho \xi \; \mathrm{D}^{\alpha-\rho} u \, \varphi \, \mathrm{d}x \\
&= (-1)^{|\alpha|} \int_\Omega \sum_{\rho \le \alpha} \left[\binom{\beta}{\rho-\gamma} + \binom{\beta}{\rho} \right] \mathrm{D}^\rho \xi \; \mathrm{D}^{\alpha-\rho} u \, \varphi \, \mathrm{d}x
\end{aligned}$$

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. □

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

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

$$(u,v)_{\mathrm{H}^k(\Omega)} \coloneqq \sum_{|\alpha| \le k} \int_\Omega \mathrm{D}^\alpha u \, \overline{\mathrm{D}^\beta v} \, \mathrm{d}x$$

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

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

All other properties of the norm are easily verified for $\| \cdot \|_{\mathrm{W}^{k,p}(\Omega)}$.
Let $(u_m)_{m \in \mathbb{N}}$ be a Cauchy sequence in $\mathrm{W}^{k,p}(\Omega)$. Then for all $|\alpha| \le k$, $(\, \mathrm{D}^\alpha u_m)_{m \in \mathbb{N}}$ is a Cauchy sequence in $\mathrm{L}^p(\Omega)$ as $\| \mathrm{D}^\alpha u_m - \mathrm{D}^\alpha u_l \|_{\mathrm{L}^p(\Omega)} \le \|u_m - u_l\|_{\mathrm{W}^{k,p}(\Omega)}$. Hence, there exists $u_\alpha \in \mathrm{L}^p(\Omega)$ with

$$\mathrm{D}^\alpha u_m \to u_\alpha \text{ in } \mathrm{L}^p(\Omega), |\alpha| \le k. \tag{3.5}$$

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

$$u_m \to u \text{ in } \mathrm{L}^p(\Omega). \tag{3.6}$$

To show that $u_\alpha = \mathrm{D}^\alpha u$, we fix $\varphi \in \mathrm{C}_0^\infty(\Omega)$ and obtain

$$\int_\Omega u\,\mathrm{D}^\alpha \varphi\,\mathrm{d}x \overset{(3.6)}{=} \lim_{m\to\infty} \int_\Omega u_m\,\mathrm{D}^\alpha \varphi\,\mathrm{d}x = \lim_{m\to\infty} (-1)^{|\alpha|} \int_\Omega \mathrm{D}^\alpha u_m \varphi\,\mathrm{d}x \overset{(3.5)}{=} (-1)^{|\alpha|} \int_\Omega u_\alpha \varphi\,\mathrm{d}x,$$

since φ, $\mathrm{D}^\alpha\varphi \in \mathrm{L}^q(\Omega)$ with $\frac{1}{p}+\frac{1}{q} = 1$. Hence, $\mathrm{D}^\alpha u = u_\alpha \in \mathrm{L}^p(\Omega)$ for all $|\alpha| \le k$ and $u \in \mathrm{W}^{k,p}(\Omega)$. But then (3.5) and (3.6) imply $u_m \to u$ in $\mathrm{W}^{k,p}(\Omega)$. Hence, $\mathrm{W}^{k,p}(\Omega)$ is complete and a Banach space.
That $(\cdot,\cdot)_{\mathrm{H}^k(\Omega)}$ is a scalar product on $\mathrm{H}^k(\Omega)$ easily follows from the L^2-scalar product. Hence, $\mathrm{H}^k(\Omega)$ is a Hilbert space. $\square$

In particular, $\mathrm{W}_0^{k,p}(\Omega)$ is a Banach space and a subspace of $\mathrm{W}^{k,p}(\Omega)$.

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