# Contents

# 1   Prior Concepts to Know

The following are just some concepts, ideas, and interesting topics (mainly in analysis) that help in understanding these notes. The main focus here is on background material required for studying Sobolev spaces and adaptive finite element methods.

## 1.1   Important inequalities

A lot of analysis proofs in general can be boiled down to finding out if some element is smaller than, bigger than, or equal to some other element. For this reason, it is very helpful to know some of these important inequalities.

**Theorem** (Young's inequality)**.** Let $p > 1$, $q < \infty$, and $\frac{1}{p} + \frac{1}{q} = 1$. Then

$$ab \leq \frac{a^p}{p} + \frac{b^q}{q}.$$

*Proof.* Suppose we $t = \frac{1}{q}$ and $(1 - t) = \frac{1}{p}$, implying $t \in (0, 1)$. Then since we know ln is a concave function, we have

$$\begin{aligned}
\ln\left((1 - t)a^p + tb^q\right) &\geq (t - 1)\ln\left(a^p\right) + t\ln\left(b^q\right) \\
&= p(t - 1)\ln\left(a\right) + qt\ln\left(b\right) \\
&= \ln\left(a\right) + \ln\left(b\right) \\
&= \ln\left(ab\right).
\end{aligned}$$

$\square$

**Theorem** (Hölder's inequality)**.** Assume $1 \leq p$, $q \leq \infty$, and $\frac{1}{p} + \frac{1}{p} = 1$. If $u \in L^p(\mathbb{R}^n)$ and $v \in L^q(\mathbb{R}^n)$, then

$$\int_{\mathbb{R}^n} |uv| dx \leq \|u\|_{L^p(\mathbb{R}^n)} \|v\|_{L^q(\mathbb{R}^n)}.$$

*Proof.* Letting $0 < t \in \mathbb{R}$, we can say

$$|uv| = |ut||v/t|,$$

and by Young's inequality

$$|uv| = |ut||v/t| \leq \frac{|ut|^p}{p} + \frac{|v/t|^q}{q} = \frac{|u|^p t^p}{p} + \frac{|u|^q}{qt^q}.$$

Now integrating with respect to $x \in \mathbb{R}^n$, results in

$$\int_{\mathbb{R}^n} |uv| dx \leq \int_{\mathbb{R}^n} \left(\frac{|u|^p t^p}{p} + \frac{|u|^q}{qt^q}\right) dx = \frac{t^p}{p}\int_{\mathbb{R}^n} |u|^p dx + \frac{1}{qt^q}\int_{\mathbb{R}^n} |v|^q dx = g(t). \quad (1)$$

For the sake of simplicity let

$$a = \int_{\mathbb{R}^n} |u|^p dx, \text{ and } b = \int_{\mathbb{R}^n} |v|^q dx.$$

Now we wish to find the smallest $t > 0$ that satisfies equation 1. To do this we can employ Calculus, which says the minimum $t$ we are looking for, which we denote as $t_0$, satisfies $g'(t_0) = 0$. First, we need to compute $g'(t)$ as follows

$$g'(t) = \frac{d}{dt}\left(\frac{t^p}{p}a + \frac{1}{qt^q}b\right) = t^{p-1}a - \frac{b}{t^{q+1}}.$$

Then, let $g'(t) = 0$ and solve for $t$ as follows

$$g'(t) = t^{p-1}a - \frac{b}{t^{q+1}} = 0$$

$$\Rightarrow t^{p-1}a = \frac{b}{t^{q+1}}$$

$$\Rightarrow t^{p-1}t^{q+1} = \frac{b}{a}$$

$$\Rightarrow t^{p+q} = \frac{b}{a}$$

$$\Rightarrow t = \left(\frac{b}{a}\right)^{\frac{1}{p+q}} = t_0.$$

Finally, compute $g(t_0)$ as follows

$$g(t_0) = \frac{\left(\left(\frac{b}{a}\right)^{\frac{1}{p+q}}\right)^p}{p}a + \frac{1}{q\left(\left(\frac{b}{a}\right)^{\frac{1}{p+q}}\right)^q}b$$

$$= \frac{\left(\frac{b}{a}\right)^{\frac{p}{p+q}}a}{p} + \frac{b}{q\left(\frac{b}{a}\right)^{\frac{q}{p+q}}}$$

$$= \frac{\left(\frac{b}{a}\right)^{\frac{p-1}{p}}a}{p} + \frac{b}{q\left(\frac{b}{a}\right)^{\frac{1}{p}}}$$

$$= \frac{b^{\frac{1}{q}}a^{\frac{1}{p}}}{p} + \frac{b^{\frac{1}{q}}a^{\frac{1}{p}}}{q}$$

$$= b^{\frac{1}{q}}a^{\frac{1}{p}}\left(\frac{1}{p} + \frac{1}{q}\right)$$

$$= b^{\frac{1}{q}}a^{\frac{1}{p}}$$

$$= \left(\int_{\mathbb{R}^n}|v|^q dx\right)^{\frac{1}{q}}\left(\int_{\mathbb{R}^n}|u|^p dx\right)^{\frac{1}{p}}$$

$$= \|v\|_{L^q(\mathbb{R}^n)}\|u\|_{L^p(\mathbb{R}^n)}.$$

$\square$

## 1.2   Banach Spaces

Banach spaces are very important for the study of Sobolev spaces as Sobolev spaces themselves are Banach spaces, which will be proven later on. Being able to prove some space is a Banach space is very helpful as Banach spaces are very nice mathematical structures that imply a lot of nice properties.

**Definition.** A *linear space* over a field $F$ (usually a subfield of the complex numbers) is a non-empty set $X$ equipped with a special element 0, three operations, and a set of axioms that the three operations must satisfy. These operations and axioms are laid out nicely for the real numbers by Professor Tao here.

**Definition.** A *normed linear space* is a linear space $X$ over a subfield $F$ of the complex numbers equipped with a norm, where the norm is a real-valued function $\|\cdot\| : X \to \mathbb{R}$ satisfying the following four axioms:

(i) $\|u + v\| \leq \|u\| + \|v\|$ for all $u, v \in X$.

(ii) $\|\lambda u\| = |\lambda|\|u\|$ for all $u \in X$ and $\lambda \in F$.

(iii) $\|u\| \geq 0$ for all $u \in V$.

(iv) $\|u\| = 0$ if and only if $u = 0$.

A normed linear space $X$ is also a *metric space* under the metric $\rho$ defined by

$$\rho(u, v) = \|u - v\|$$

for all $u, v \in X$.

**Definition.** A *complete metric space* is a metric space $X$ where every Cauchy sequence of points in $X$ converge to a point also in $X$. i.e. a space that has no missing points.

**Definition.** A *Banach space* is a complete normed linear space.

## 1.3   Hilbert spaces

Let $H$ be a real linear space.

**Definition.** A mapping $(\cdot, \cdot) : H \times H \to \mathbb{R}$ is called an *inner product* if

1. $(u, v) = (v, u)$ for all $u, v \in H$,

2. $u \mapsto (u, v)$ is linear for each $v \in H$,

3. $(u, v) \geq 0$ for all $v \in H$,

4. $(u, u) = 0$ if and only if $u = 0$.

**Definition.** The inner product is also related to the norm of $H$ as

$$\|u\| = (u, u)^{1/2}, \tag{2}$$

and by the Cauchy-Schwarz inequality, we have

$$|(u, v)| \leq \|u\|\|v\| \tag{3}$$

for all $u, v \in H$. Equation 3 verifies that equation 2 defines a norm on $H$.

**Definition.** A *Hilbert space* $H$ is a Banach space equipped with an inner product which defines the norm on $H$.

**Theorem** (Riesz Representation Theorem)**.** For every bounded linear functional $F$ on a Hilbert space $H$, there exists a uniquely determined element $f \in H$ such that $F(x) = (x, f)$ for all $x \in H$. Furthermore, $\|F\|_{\text{op}} = \|f\|_H$.

*Proof.* In progress...                                                                          $\square$

**Theorem** (Lax-Milgram Theorem)**.** Let $B$ be a bounded, coercive bilinear form on a Hilbert space $H$. Then for every bounded linear functional $F$ on $H$ there exists a uniquely determined element $f \in H$ such that $B(x, f) = F(x)$ for all $x \in H$.

*Proof.* In progress...                                                                          $\square$

## 1.4   Hölder spaces

Hölder spaces are function spaces which contain well-behaved functions, and where the function space itself is a Banach space. Functions being well-behaved in this case just means they are differentiable and continuous to certain degrees. Hölder spaces become relevant when discussing Sobolev inequalities.

**Definition** (Hölder continuous functions)**.** Assume $U \subset \mathbb{R}^n$ is open and $0 < \gamma \leq 1$. *Lipschitz continuous functions* $u : U \to \mathbb{R}$ satisfy the estimate

$$|u(x) - u(y)| \leq C|x - y|$$

where $x, y \in U$ and $C$ is some constant. Now with the same assumptions, consider the variant

$$|u(x) - u(y)| \leq C|x - y|^\gamma,$$

where $u$ is now said to be *Hölder continuous with exponent* $\gamma$.

**Definition** (Supremum norm and $\gamma^{th}$-Hölder seminorm)**.**   (i) If $u : U \to \mathbb{R}$ is bounded and continuous, the supremum norm is denoted

$$\|u\|_{C(\overline{U})} = \sup_{x \in U} |u(x)|.$$

(ii) The $\gamma^{th}$-Hölder seminorm of $u : U \to \mathbb{R}$ is

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

and the $\gamma^{th}$-Hölder norm is

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

**Definition.** The Hölder space $C^{k,\gamma}(\overline{U})$ consists of all functions $u \in C^k(\overline{U})$, where the norm

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

**Theorem** (Hölder spaces as function spaces)**.** The space of functions $C^{k,\gamma}(\overline{U})$ is a Banach space.

*Proof.* Problem 5.1.                                                                                      □

## 2   Sobolev Spaces

Sobolev spaces are motivated by the study of elliptic PDEs, for example, the Poisson equation

$$\Delta u = f.$$

Multiplying this equation on both sides by $\phi \in C_c^\infty$, then integrating both sides, then integrating the left side by parts, results in

$$\int \phi \Delta u = \int \phi f$$

$$\Rightarrow \int \phi \nabla^2 u = \int \phi f$$

$$\Rightarrow \phi \nabla u - \int \phi \nabla u = \int \phi f$$

$$\Rightarrow -\int \phi \nabla u = \int \phi f.$$

It can then be shown that for any $u \in C^2$, if the above integral relation holds, then $u$ is a classical solution of the original equation. However, one may notice that the integral relation only needs $\nabla u \in L^p$, for some fixed $p$, to be satisfied. Also, one may notice the similarity of the integral relation to the definition of weak derivatives. Both these observations lead to a more generalized case where $u \in L_{\text{loc}}^1$ and $u \notin C^1$, only requiring that the $\alpha^{th}$-weak partial derivative of $u$ belong to $L^p$, for some fixed $p$. This more generalized case gives rise to our formal definition of Sobolev spaces.

## 2.1   Definition of the $W^{k,p}$ spaces

Fix $1 \leq p \leq \infty$, let $k \in \mathbb{N}$, and let $U \subset \mathbb{R}^n$ be a bounded open set.

**Definition.** The Sobolev space

$$W^{k,p}(U) = \{u \in L^1_{\text{loc}}(U) \,|\, D^\alpha u \text{ exists in the weak sense, and } D^\alpha u \in L^p(U) \,\forall\, |\alpha| \leq k\},$$

consists of all locally summable functions $u : U \to \mathbb{R}$ such that for each $|\alpha| \leq k$, $D^\alpha u$ exists in the weak sense and belongs to $L^p(U)$.

**Remark.** When $p = 2$ we will instead use the notation

$$W^{k,2}(U) = H^k(U),$$

because this Sobolev space is also a Hilbert space.

**Definition.** If $u \in W^{k,p}(U)$, we define its norm to be

$$\|u\|_{W^{k,p}(U)} = \sum_{|\alpha| \leq k} \|D^\alpha u\|_{L^p(U)}.$$

**Theorem** (Sobolev spaces as function spaces). For each $k \in \mathbb{N}$ and $1 \leq p \leq \infty$, the Sobolev space $W^{k,p}(U)$ is a Banach space.

*Proof.* In progress...                                                                 $\square$

## 2.2  Approximation

Sobolev spaces are nice function spaces as we find that elements in Sobolev spaces can be approximated by sequences of smooth functions. These approximations can be done locally, globally up to but excluding the boundary, and globally up to and including the boundary. As expected these require three different Theorems (taken from Evans) which increase in difficulty to prove.

**Theorem** (Local approximation by smooth functions)**.** Let $U \subset \mathbb{R}^n$ be a bounded open set. Suppose $u \in W^{k,p}(U)$ for some $1 \leq p < \infty$, and set

$$u^\epsilon = \eta_\epsilon * u \text{ in } U_\epsilon.$$

Then

(i)  $u^\epsilon \in C^\infty(U_\epsilon)$  $\forall \epsilon > 0$, and

(ii)  $u^\epsilon \to u$ in $W^{k,p}_{\text{loc}}(U)$, as $\epsilon \to 0$.

*Proof.*  In progress...                                                       $\square$

**Theorem** (Global approximation by smooth functions)**.** Let $U \subset \mathbb{R}^n$ be a bounded open set. Suppose $u \in W^{k,p}(U)$ for some $1 \leq p < \infty$. Then there exists functions $u_m \in C^\infty(U) \cap W^{k,p}(U)$ such that
$$u_m \to u \text{ in } W^{k,p}(U).$$

*Proof.*  In progress...                                                       $\square$

Since $U \subset \mathbb{R}^n$ is a bounded open set, this Theorem says nothing about the smoothness of the boundary of $U$, which is the goal of the next Theorem.

**Theorem** (Global approximation by functions smooth up to the boundary)**.** Let $U \subset \mathbb{R}^n$ be a bounded open set. Suppose $\partial U$ is $C^1$ and suppose $u \in W^{k,p}(U)$ for some $1 \leq p < \infty$. Then there exists functions $u_m \in C^\infty(\overline{U})$ such that

$$u_m \to u \text{ in } W^{k,p}(U).$$

*Proof.*  In progress...                                                       $\square$

## 2.3   Extensions

Naturally we should desire to extend functions in $W^{k,p}(U)$ to functions in $W^{k,p}(\mathbb{R}^n)$. Evans discusses and proves this extension which becomes useful for some of the Sobolev inequalities proofs.

**Theorem.** Suppose $1 \leq p \leq \infty$. Let $U \subset \mathbb{R}^n$ be a bounded open set, where $\partial U$ is $C^1$. Let $V \subset \mathbb{R}^n$ be a bounded open set such that $U \subset\subset V$. Then there exists a bounded linear operator

$$E : W^{1,p}(U) \to W^{1,p}(\mathbb{R}^n)$$

such that $\forall u \in W^{1,p}(U)$:

  (i)  $Eu = u$ a.e. in $U$,

  (ii)  $Eu$ has support within $V$, and

  (iii)  $\|Eu\|_{W^{1,p}(\mathbb{R}^n)} \leq C(p, U, V)\|u\|_{W^{1,p}(U)}$.

*Proof.* In progress... □

## 2.4 Sobolev inequalities

Sobolev inequalities are useful for finding embeddings of Sobolev spaces in other function spaces that may be easier to work with, more desirable, or simply imply nice properties. Many of the following theorems are taken from Evans.

**Theorem** (Gagliardo-Nirenberg-Sobolev inequality)**.** Suppose $1 \leq p < n$. There exists a constant $C(p,n) > 0$ such that

$$\|u\|_{L^{p^*}(\mathbb{R}^n)} \leq C(p,n)\|Du\|_{L^p(\mathbb{R}^n)},$$

for all $u \in C_c^1(\mathbb{R}^n)$.

*Proof.* In progress... $\qquad\square$

**Theorem** (Estimates for $W^{1,p}$, where $1 \leq p < n$)**.** Let $U \subset \mathbb{R}^n$ be a bounded open set, and suppose $\partial U$ is $C^1$. Suppose $u \in W^{1,p}(U)$ for some $1 \leq p < n$. It then follows that $u \in L^{p^*}$, with the estimate that

$$\|u\|_{L^{p^*}(U)} \leq C(p,n,U)\|u\|_{W^{1,p}(U)},$$

where $C(p,n,U) > 0$ is a constant.

*Proof.* In progress... $\qquad\square$

**Theorem** (Estimates for $W_0^{1,p}$, where $1 \leq p < n$)**.** Let $U \subset \mathbb{R}^n$ be a bounded open set. Suppose $u \in W_0^{1,p}(U)$ for some $1 \leq p < n$. Then we get the estimate

$$\|u\|_{L^q(U)} \leq C(p,q,n,U)\|Du\|_{L^p(U)},$$

for all $1 \leq q \leq p^*$, where $C(p,q,n,U) > 0$ is a constant.

*Proof.* In progress... $\qquad\square$

**Remark.** If $U$ is bounded as we supposed, then on $W_0^{1,p}$, the norm $\|Du\|_{L^p} \equiv \|u\|_{W^{1,p}(U)}$, meaning this is still an estimate for functions in Sobolev spaces.

**Theorem** (Morrey's inequality)**.** Suppose $n < p \leq \infty$. Then there exists a constant $C(p,n) > 0$ such that
$$\|u\|_{C^{0,\gamma}(\mathbb{R}^n)} \leq C(p,n)\|u\|_{W^{1,p}(\mathbb{R}^n)},$$
for all $u \in W^{1,p}(U)$ with $u \in C^1(\mathbb{R}^n)$, where $\gamma = 1 - \frac{n}{p}$.

*Proof.* In progress... $\qquad\square$

**Theorem** (Estimates for $W^{1,p}$, where $n < p \leq \infty$)**.** Let $U \subset \mathbb{R}^n$ be a bounded open set, and suppose $\partial U$ is $C^1$. Suppose $u \in W^{1,p}(U)$ for some $n < p \leq \infty$. It then follows that a continuous version $u^* \in C^{0,\gamma}(\overline{U})$, where $\gamma = 1 - \frac{n}{p}$, with the estimate that

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

where $C(p,n,U) > 0$ is a constant.

*Proof.* In progress... $\qquad\square$

# 3   Notation

(i) A *multiindex* is a vector $\alpha = (\alpha_1, \ldots, \alpha_n)$ where each component $\alpha_i \in \mathbb{N}_0$. A multi-index has an order defined by

$$|\alpha| = \alpha_1 + \cdots + \alpha_n.$$

(ii) Using our definition of a multiindex and letting $u(x)$ be some function, we define

$$D^\alpha u(x) = \frac{\partial^{|\alpha|} u(x)}{\partial x_1^{\alpha_1} \ldots \partial x_n^{\alpha_n}} = \partial_{x_1}^{\alpha_1} \ldots \partial_{x_n}^{\alpha_n} u(x).$$

(iii) Let $U, V \subset \mathbb{R}^n$. Then define

$$V \subset\subset U$$

to be when $V \subset \overline{V} \subset U$ and $\overline{V}$ is compact. In plain english this means $V$ is *compactly contained* in $U$.

(iv) Let $f$ and $g$ be functions. Then define $*$ to be the *convolution operator* where

$$(f * g)(x) = \int_{-\infty}^{\infty} f(\tau)g(x - \tau)d\tau = \int_{-\infty}^{\infty} f(x - \tau)g(\tau)d\tau$$

is the *convolution* of the functions $f$ and $g$ which results in a third function that expresses how one of the functions modifies the other. Note that I am assuming $f$ and $g$ are both supported on an infinite interval, which may not always be the case.

(v) Let $u(x)$ be a function where $x \in \mathbb{R}^n$. Then the *gradient vector* of $u$ is

$$Du(x_1, \ldots, x_n) = (u_{x_1}, \ldots, u_{x_n}).$$