

Partial Differential Equations
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Please note that I write this lecture notes for my personal use. I may write things differently than presented in the lecture. This script also contains some of my personal solutions for exercises (which may be wrong).

Chapter 1

Introduction

A differential equation is an equation of a function and its derivatives.

Example 1.1 (Linear ODE) Let $f : \mathbb{R} \rightarrow \mathbb{R}$,

$$\begin{cases} f'(t) = af(t) \text{ for all } t \geq 0, a \in \mathbb{R} \\ f(0) = a_0 \end{cases}$$

is a linear ODE (Ordinary differential equation). The solution is: $f(t) = a_0 e^{at}$ for all $t \geq 0$.

Example 1.2 (Non-Linear ODE) $f : \mathbb{R} \rightarrow \mathbb{R}$

$$\begin{cases} f'(t) = 1 + f^2(t) \\ f(0) = 1 \end{cases}$$

Lets consider $f(t) = \tan(t) = \frac{\sin(t)}{\cos(t)}$. Then we have

$$f'(t) = \frac{1}{\cos^2(t)} = 1 + \tan^2(t) = 1 + f^2(t),$$

but this solution only is *good* in $(-\pi, \pi)$. It's a problem to extend this to $\mathbb{R} \rightarrow \mathbb{R}$.

A PDE (Partial Differential Equation) is an equation of a function of 2 or more variables and its derivatives.

Remark 1.3 Recall for $\Omega \subseteq \mathbb{R}^d$ open and $f : \Omega \rightarrow \{\mathbb{R}, \mathbb{C}\}$ the notation of partial derivatives:

- $\partial_{x_i} f(x) = \lim_{h \rightarrow 0} \frac{f(x + he_i) - f(x)}{h}$, where $e_i = (0, 0, \dots, 1, \dots, 0, 0) \in \mathbb{R}^d$
- $D^\alpha f(x) = \partial_{x_1}^{\alpha_1} \cdots \partial_{x_d}^{\alpha_d} f(x)$, where $\alpha \in \mathbb{N}^d$
- $Df = \nabla f = (\partial_{x_1}, \dots, \partial_{x_d})$
- $\Delta f = \partial_{x_1}^2 + \cdots + \partial_{x_d}^2 f$
- $D^k f = (D^\alpha f)_{|\alpha|=k}$, where $|\alpha| = \sum_{i=1}^d |\alpha_i|$
- $D^2 f = (\partial_{x_i} \partial_{x_j} f)_{1 \leq i, j \leq d}$

Definition 1.4 Given a function F . Then the equation of the form

$$F(D^k u(x), D^{k-1} u(x), \dots, Du(x), u(x), x) = 0$$

with the unknown function $u : \Omega \subseteq \mathbb{R}^d \rightarrow \mathbb{R}$ is called a *PDE of order k* .

- Equations $\sum_d a_\alpha(x) D^\alpha u(x) = 0$, where a_α and u are unknown functions are called *Linear PDEs*.
- Equations $\sum_{|\alpha|=k} a_\alpha(x) D^\alpha u(x) + F(D^{k-1} u, D^{k-2} u, \dots, Du, u, x) = 0$ are called *semi-linear PDEs*.

Goals: For *solving a PDE* we want to

- Find an explicit solution! This is in many cases impossible.
- Prove a *well-posed theory* (existence of solutions, uniqueness of solutions, continuous dependence of solutions on the data)

We have two notations of solutions:

1. Classical solution: The solution is continuous differentiable (e.g. $\Delta u = f \rightsquigarrow u \in C^2$)
2. Weak Solutions: The solution is not smooth/continuous

Definition 1.5 (Spaces of continuous and differentiable functions) Let $\Omega \subseteq \mathbb{R}^d$ be open

$$C(\Omega) = \{f : \Omega \rightarrow \mathbb{R} \mid f \text{ continuous}\}$$

$$C^k(\Omega) = \{f : \Omega \rightarrow \mathbb{R} \mid D^\alpha f \text{ is continuous for all } |\alpha| \leq k\}$$

Classical solution of a PDE of order $k \rightsquigarrow C^k$ solutions!

$$L^p(\Omega) = \left\{ f : \Omega \rightarrow \mathbb{R} \text{ Lebesgue measurable} \mid \int_\Omega |f|^p d\lambda < \infty, 1 \leq p < \infty \right\}$$

Sobolev Space:

$$W^{k,p}(\Omega) = \{f \in L^p(\Omega) \mid \forall \alpha \in \mathbb{N}^n \text{ with } |\alpha| \leq k : D^\alpha f \in L^p(\Omega) \text{ exists}\}$$

In this course we will investigate

- Laplace / Poisson Equation: $-\Delta u = f$
- Heat Equation: $\partial_t u - \Delta u = f$
- Wave Equation: $\partial_t^2 u - \Delta u = f$
- Schrödinger Equation: $i\partial_t u - \Delta u = f$

Chapter 2

Laplace / Poisson Equation

2.1 Laplace Equation

$-\Delta u = 0$ (Laplace) or $-\Delta u = f(x)$ (Poisson).

Definition 2.1 (Harmonic Function) Let Ω be an open set in \mathbb{R}^d . If $u \in C^2(\Omega)$ and $\Delta u = 0$ in Ω , then u is a harmonic function in Ω .

Theorem 2.2 (Gauss-Green Theorem) Let $A \subseteq \mathbb{R}^d$ open, $\vec{F} \in C^1(A, \mathbb{R}^d)$ and $K \subseteq A$ compact with C^1 boundary. Then

$$\int_{\partial K} \vec{F} \cdot \vec{\nu} \, dS(x) = \int_K \operatorname{div}(\vec{F}) \, dx$$

where ν is the outward unit normal vector field on ∂K . Thus

$$\int_{\partial V} \nabla u \cdot \vec{\nu} \, dS(x) = \int_V \operatorname{div}(\nabla u) \, dx = \int_V \Delta u(x) \, dx$$

for any $V \subseteq \Omega$ open.

Theorem 2.3 (Green's Identities) Let $A \subseteq \mathbb{R}^d$ open, $K \subseteq A$ d-dim. compactum with C^1 boundary and $f, g \in C^2(A)$

1. Green's first identity (Integration by parts):

$$\int_K \nabla f \cdot \nabla g \, dx = \int_{\partial K} f \frac{\partial g}{\partial \nu} \, dS - \int_K f \Delta g \, dx$$

where $\frac{\partial g}{\partial \nu} = \partial_\nu g = \nu \cdot \nabla g$

2. Green's second identity:

$$\int_K f \Delta g - (\Delta f)g \, dx = \int_{\partial K} \left(f \frac{\partial g}{\partial \nu} - g \frac{\partial f}{\partial \nu} \right) \, dS$$

Exercise 2.4 Let $\Omega \subseteq \mathbb{R}^d$ open, let $f : \Omega \rightarrow \mathbb{R}$ be continuous. Prove that if $\int_B f(x) \, dx = 0$, then $u \equiv 0$ in Ω .

Theorem 2.5 (Fundamental Lemma of Calculus of Variations) Let $\Omega \subseteq \mathbb{R}^d$ open, let $f \in L^1(\Omega)$. If $\int_B f(x) \, dx = 0$ for all $x \in B_r(x) \subseteq \Omega$, then $f(x) = 0$ a.e. (almost everywhere) $x \in \Omega$.

Remark 2.6 (Solving Laplace Equation) $-\Delta u = 0$ in \mathbb{R}^d . Consider the case when u is radial, i.e. $u(x) = v(|x|)$, $v : \mathbb{R} \rightarrow \mathbb{R}$. Denote $r = |x|$, then

$$\frac{\partial r}{\partial x} = \frac{\partial}{\partial x_i} \left(\sqrt{x_1^2 + \cdots + x_d^2} \right) = \frac{2x_i}{2\sqrt{x_1^2 + \cdots + x_d^2}} = \frac{x_i}{r}$$

Then

$$\begin{aligned} \partial_{x_i} u &= \partial_{x_i} v = (\partial_r v) \frac{\partial r}{\partial x_i} = v'(r) \frac{x_i}{r} \\ \partial_{x_i}^2 u &= \partial_{x_i} \left(v(r) \frac{x_i}{r} \right) = (\partial_{x_i} v(r))' \frac{x_i}{r} + v'(r) \partial_{x_i} \left(\frac{x_i}{r} \right) \\ &= (\partial_r v'(r)) \left(\frac{dr}{\partial x_i} \right) \frac{x_i}{r} + v'(r) \left(\frac{1}{r} - \frac{x_i}{r^2} (\partial_{x_i} r) \right) = v'(r) \frac{x_i^2}{r^2} + v'(r) \left(\frac{1}{r} - \frac{x_i^2}{r^3} \right) \end{aligned}$$

So we have $\Delta u = \left(\sum_{i=1}^d \partial_{x_i}^2 \right) u = v''(r) + v'(r) \left(\frac{d}{r} - \frac{1}{r} \right)$

Thus $\Delta u = v'(r) + v(r) \frac{d-1}{r}$. We consider $d \geq 2$. Laplace operator $\Delta u = 0$ now becomes $v''(r) + v'(r) \frac{d-1}{r} = 0$

$$\begin{aligned} \Rightarrow \log(v(r))' &= \frac{v'(r)}{v(r)} = -\frac{d-1}{r} = -(d-1)(\log r)' \quad (\text{recall } \log(f)' = \frac{f'}{f}) \\ \Rightarrow v'(r) &= \frac{1}{v^{d-2} + \text{const.}} \end{aligned}$$

$$\begin{cases} \frac{\text{const}}{r^{d-2}} + \text{const}x + \text{const} & , d \geq 3 \\ \text{const} \log(r) + \text{const}x + \text{const} & , d = 2 \end{cases}$$

Definition 2.7 (Fundamental Solution of Laplace Equation)

$$\Phi(x) = \begin{cases} -\frac{1}{2\pi} \log(|x|), & d = 2 \\ \frac{1}{(d-2)d|B_1|} \frac{1}{|x|^{d-2}}, & d \geq 3 \end{cases}$$

Where $|B_1|$ is the Volume of the ball $B_1(0) = B(0, 1) \subseteq \mathbb{R}^d$.

Remark 2.8 $\Delta \Phi(x) = 0$ for all $x \in \mathbb{R}^d$ and $x \neq 0$.

2.2 Poisson-Equation

The Poisson-Equation is $-\Delta u(x) = f(x)$ in \mathbb{R}^d . The explicit solution is given by

$$u(x) = (\Phi \star f)(x) = \int_{\mathbb{R}^d} \Phi(x-y) f(y) dy = \int_{\mathbb{R}^d} \Phi(y) f(x-y) dy$$

This can be heuristically justified with

$$-\Delta(\Phi \star f) = (-\Delta \Phi) \star f = \delta_0 \star f = f$$

Theorem 2.9 Assume $f \in C_c^2(\mathbb{R}^d)$. Then $u = \Phi \star f$ satisfies that $u \in C^2(\mathbb{R}^d)$ and $-\Delta u(x) = f(x)$ for all $x \in \mathbb{R}^d$

Proof. By definition we have

$$u(x) = \int_{\mathbb{R}^d} \Phi(y) f(x-y) dy.$$

First we check that u is continuous: Take $x_k \rightarrow x_0$ in \mathbb{R}^d . We prove that $u(x_n) \xrightarrow{n} u_0$, i.e.

$$\lim_{n \rightarrow \infty} \int_{\mathbb{R}^d} \Phi(y) f(x_n - y) dy = \int_{\mathbb{R}^d} \Phi(y) f(x_0 - y) dy$$

This follows from the Dominated Convergence Theorem. More precisely:

$$\lim_{n \rightarrow \infty} \Phi(y) f(x_n - y) = \Phi(y) f(x_0 - y) \quad \text{for all } y \in \mathbb{R}^d \setminus \{0\}$$

and

$$|\Phi(y) f(x - y)| \leq \|f\|_{L^\infty} \cdot \mathbb{1}(|y| \leq R) \cdot |\Phi(y)| \in L^1(\mathbb{R}^d, dy)$$

where $R > 0$ depends on $\{x_n\}$ and $\text{supp}(f)$ but independent of y . Now we compute the derivatives:

$$\begin{aligned} \partial_{x_i} u(x) &= \partial_{x_i} \int_{\mathbb{R}^d} \Phi(y) f(x - y) dy = \lim_{h \rightarrow 0} \int_{\mathbb{R}^d} \Phi(y) \frac{f(x + h e_i - y) - f(x - y)}{h} dy \\ (\text{dom. conv.}) &= \int_{\mathbb{R}^d} \Phi(y) \partial_{x_i} f(x - y) dy \\ \Rightarrow D^\alpha u(x) &= \int_{\mathbb{R}^d} \Phi(y) D_x^\alpha f(x - y) dy \quad \text{for all } |\alpha| \leq 2 \end{aligned}$$

$D^\alpha u(x)$ is continuous, thus $u \in C^2(\mathbb{R}^d)$. Now we check if this solves the Poisson-Equation:

$$\begin{aligned} -\Delta u(x) &= \int_{\mathbb{R}^d} \Phi(y) (-\Delta_x) f(x - y) dy = \int_{\mathbb{R}^d} \Phi(y) (-\Delta_y) f(x - y) dy \\ &= \int_{\mathbb{R}^d \setminus B(0, \epsilon)} \Phi(y) (-\Delta_x) f(x - y) dy + \int_{B(0, \epsilon)} \Phi(y) (-\Delta_x) f(x - y) dy \quad (\epsilon > 0 \text{ small}) \end{aligned}$$

Now we come to the main part. We apply integration by parts (2.3):

$$\begin{aligned} &\int_{\mathbb{R}^d \setminus B(0, \epsilon)} \Phi(y) (-\Delta_y) f(x - y) dy \\ &= \int_{\mathbb{R}^d \setminus B(0, \epsilon)} (\nabla_y \Phi(y)) \cdot \nabla_y f(x - y) dy - \int_{\partial B(0, \epsilon)} \Phi(y) \cdot \frac{\partial f}{\partial \vec{n}}(x - y) dS(y) \\ &= \int_{\mathbb{R}^d \setminus B(0, \epsilon)} \underbrace{(-\Delta_y \Phi(y))}_{=0} f(x - y) dy \\ &\quad + \int_{\partial B(0, \epsilon)} \frac{\partial \Phi}{\partial \vec{n}}(y) f(x - y) dS(y) - \int_{\partial B(0, \epsilon)} \Phi(y) \frac{\partial f}{\partial \vec{n}}(x - y) dS(y) \end{aligned}$$

We have that $\nabla_y \Phi(y) = -\frac{1}{d|B_1|} \frac{y}{|y|^d}$ and $\vec{n} = \frac{y}{|y|}$ in $\partial B(0, \epsilon)$. This leads to

$$\frac{\partial \Phi}{\partial \vec{n}} = \frac{1}{d|B_1|} \frac{1}{|y|^{d-1}} = \frac{1}{d|B_1| \epsilon^{d-1}} \quad \text{for } y \in \partial B(0, \epsilon)$$

Hence:

$$\begin{aligned} &\int_{\partial B(0, \epsilon)} \frac{\partial \Phi}{\partial \vec{n}}(y) f(x - y) dS(y) = \frac{1}{d|B_1| \epsilon^{d-1}} \int_{\partial B(0, \epsilon)} f(x - y) dS(y) \\ &= \oint_{\partial B(0, \epsilon)} f(x - y) dS(y) = \oint_{\partial B(x, \epsilon)} f(y) dS(y) \xrightarrow{\epsilon \rightarrow 0} f(x) \end{aligned}$$

We have to regard the following error terms:

$$\begin{aligned}
\bullet \left| \int_{B(0,\epsilon)} \Phi(y) (-\Delta_y) f(x-y) dy \right| &\leq \int_{B(0,\epsilon)} |\Phi(y)| \underbrace{|-\Delta_y f(x-y)|}_{\leq \|\Delta f\|_{L^\infty} \mathbb{1}(|y| \leq R)} dy \\
&\leq \|\Delta f\|_{L^\infty} \int_{\mathbb{R}^d} \underbrace{|\Phi(y)| \mathbb{1}(|y| \leq R)}_{L^1(\mathbb{R}^d)} \mathbb{1}(|y| \leq \epsilon) \xrightarrow{\epsilon \rightarrow 0} 0
\end{aligned}$$

Where $R > 0$ depends on x and the support of f but is independent of y .

$$\begin{aligned}
\bullet \left| \int_{\partial B(0,\epsilon)} \Phi(y) \frac{\partial f}{\partial \vec{n}}(x-y) dS(y) \right| &\leq \|\nabla f\|_{L^\infty} \int_{\partial B(0,\epsilon)} |\Phi(y)| dy \\
&\leq \begin{cases} \text{const} \cdot \epsilon |\log \epsilon| \rightarrow 0, & d = 2 \\ \text{const} \cdot \epsilon \rightarrow 0, & d \geq 3 \end{cases}
\end{aligned}$$

Conclusion: $-\Delta u(x) = f(x)$ for all $x \in \mathbb{R}^d$ proved that $u = \Phi \star f$ and $f \in C_c^2(\mathbb{R}^d)$. ■

Thus, if $f \in C_c^2(\mathbb{R})$, then $u = \Phi \star f$ satisfies $u \in C^2(\mathbb{R}^2)$ and $-\Delta u(x) = f(x)$ for all $x \in \mathbb{R}^d$.

Remark 2.10 The result holds for a much bigger class of functions f . For example if $f \in C_c^1(\mathbb{R})$ we can easily extend the previous proof:

$$\partial_{x_i} u = \int_{\mathbb{R}^d} \Phi(y) \partial_{x_i} f(x-y) dy \in C(\mathbb{R}^d) \Rightarrow u \in C^1(\mathbb{R}^d)$$

Consequently:

$$\partial_{x_i} \partial_{x_j} u = \partial_{x_i} \int_{\mathbb{R}^d} \Phi(y) \partial_{x_j} f(x-y) dy = \int_{\mathbb{R}^d} \partial_{x_i} \Phi(y) \partial_{x_j} f(x-y) dy \in C(\mathbb{R}^d)$$

So we have $u \in C^2(\mathbb{R}^d)$. Now we can compute

$$\Delta u = \sum_{i=1}^d \int_{\mathbb{R}^d} \partial_{x_i} \Phi(y) \partial_{x_i} f(x-y) dy \stackrel{(IBP)}{=} f(x).$$

Exercise 2.11 Extend this to more general functions!

2.3 Equations in general domains

Theorem 2.12 (Mean Value Theorem for Harmonic Functions) Let $\Omega \subseteq \mathbb{R}^d$ be open, let $u \in C^2(\Omega)$ and $\Delta u = 0$ in Ω . Then

$$u(x) = \oint_{B(x,r)} u = \oint_{\partial B(x,r)} u \quad \text{for all } x \in \Omega, B(x,r) \subseteq \Omega$$

Proof. Consider all $r > 0$ s.t. $B(x,r) \subseteq \Omega$,

$$f(r) = \oint_{\partial B(x,r)} u$$

We need to prove that $f(r)$ is independent of r . When it is done, then we immediately obtain

$$f(r) = \lim_{t \rightarrow 0} f(t) = u(x)$$

as u is continuous. To prove that, consider

$$\begin{aligned}
f'(r) &= \frac{d}{dr} \left(\oint_{\partial B(0,r)} u(x+y) dS(y) \right) \\
&= \frac{d}{dr} \left(\oint_{\partial B(0,1)} u(x+rz) dS(z) \right) \\
(\text{dom. convergence}) \quad &= \oint_{\partial B(0,1)} \frac{d}{dr} [u(x+rz)] dS(z) \\
&= \oint_{\partial B(0,1)} \nabla u(x+rz) z dS(z) \\
&= \oint_{\partial B(x,r)} \nabla u(y) \frac{y-x}{r} dS(y) \\
&= \frac{1}{|B(x,r)|_{\mathbb{R}^d}} \int_{\partial B(x,r)} \nabla \cdot u(y) \cdot \vec{n}_y dS(y) \\
(\text{Gauss-Green 2.2}) \quad &= \frac{1}{|B(x,r)|_{\mathbb{R}^d}} \int_{B(x,r)} \underbrace{(\Delta u)(y)}_{=0} dy = 0 \quad \blacksquare
\end{aligned}$$

Exercise 2.13 In 1D: $\Delta u = 0 \Leftrightarrow u'' = 0 \Leftrightarrow u(x) = ax + b$ (Linear Equation)

Remark 2.14 Recall the polar decomposition. Let $x \in \mathbb{R}^d, x = (r, w), r = |x| > 0, w \in S^{d-1}$, then

$$\int_{B(0,r)} g(y) dy = \int_0^r \left(\int_{B(0,s)} g(y) dS(y) \right) ds$$

Remark 2.15 We already proved that for u harmonic we have $u(x) = \oint_{\partial B(x,r)} u dy$. Now we have

$$\begin{aligned}
\int_{B(x,r)} u(y) dy &= \int_{B(0,r)} u(x+y) dy \\
(\text{Pol. decomposition}) \quad &= \int_0^r \left(\int_{\partial B(0,s)} u(x+y) dS(y) \right) ds \\
&= \int_0^r \left(\int_{\partial B(x,s)} u(y) dS(y) \right) ds \\
(\text{Mean value property}) \quad &= \int_0^r (|\partial B(x,s)| u(x)) ds = |B(x,r)| u(x)
\end{aligned}$$

This implies

$$\oint_{B(x,r)} u(y) dy = u(x) \quad \text{for any } B(x,r) \subseteq \Omega.$$

Remark 2.16 The reverse direction is also correct, namely if $u \in C^2(\Omega)$ and

$$u(x) = \oint_{B(x,r)} u(y) dy = \oint_{\partial B(x,r)} u(y) dy \quad \text{for all } B(x,r) \subseteq \Omega,$$

then u is harmonic, i.e. $\Delta u = 0$ in Ω . (The proof is exactly like before)

Theorem 2.17 (Maximum Principle) Let $\Omega \subseteq \mathbb{R}^d$ be open, let $u \in C^2(\Omega) \cap C(\bar{\Omega})$, $\Delta u = 0$ in Ω . Then

- a) $\max_{x \in \bar{\Omega}} u(x) = \max_{x \in \partial\Omega} u(x)$
- b) Assume that Ω is connected. Then if there is a $x_0 \in \Omega$ s.t. $u(x_0) = \max_{x \in \bar{\Omega}} u(x)$, then $u \equiv \text{const.}$ in Ω .

Proof. Given $U \subseteq \mathbb{R}^d$ open, we can write $U = \bigcup_i U_i$, where U_i is open and connected.

- b) Assume that Ω is connected and there is a $x_0 \in \Omega$ s.t. $u(x_0) = \sup_{y \in \Omega} u(y)$. Define $U = \{x \in \Omega \mid u(x) = u(x_0)\} = u^{-1}(u(x_0))$. U is closed since u is continuous. Moreover, U is open by the mean-value theorem. I.e. for all $x \in U$ there is a $r > 0$ s.t. $B(x, r) \subseteq U \subseteq \Omega$. Since U is connected we get $U = \Omega$, so u is constant in Ω . On the other hand, if there is no $x_0 \in \Omega$ s.t. $u(x_0) = \sup_{x \in \Omega} u(x)$ we have $\forall x_0 \in \Omega : u(x) < \sup_{x \in \bar{\Omega}} u(x) = \sup_{x \in \partial\Omega} u(x)$
- a) Given $\Omega \subseteq \mathbb{R}^d$ open, we can write $\Omega = \bigcup_i \Omega_i$, where Ω_i is open and connected. By b) we have

$$\sup_{x \in \bar{\Omega}_i} u(x) = \sup_{x \in \partial\Omega_i} u(x), \quad \forall i$$

So we can conclude

$$\sup_{x \in \bar{\Omega}} u(x) = \sup_{x \in \partial\Omega} u(x). \quad \blacksquare$$

Definition 2.18 • If $\Omega \subseteq \mathbb{R}^d$ is open, $u \in C^2(\Omega)$, then u is called *sub-harmonic* if $\Delta u \geq 0$ in Ω .

- If $\Delta u \leq 0$, then u is called *super-harmonic*.

Exercise 2.19 (E 1.4) Let $\Omega \subseteq \mathbb{R}^d$ be open and $u \in C^2(\Omega)$ be subharmonic.

- a) Prove that u satisfies the Mean Value Inequality

$$\oint_{\partial B(x, r)} u(y) dS(y) \geq \int_{B(x, r)} u(y) dy \geq u(x)$$

for all $B(x, r) \subseteq \mathbb{R}^d$.

- b) Assume further that Ω is connected and $u \in C(\bar{\Omega})$. Prove that u satisfies the strong maximum principle, namely either
 - u is constant in Ω , or
 - $\sup_{y \in \partial\Omega} u(y) > u(x)$ for all $x \in \Omega$.

My Solution. a) Let $f(r) = \oint_{\partial B(x,r)} u(y) dS(y)$, then we have

$$\begin{aligned}
\partial_r f(r) &= \partial_r \oint_{\partial B(x,r)} u(y) dS(y) \\
(\text{Dom. Convergence}) \quad &= \oint_{\partial B(x,r)} \partial_r u(y) dS(y) \\
&= \oint_{\partial B(0,1)} \partial_r u(x + yr) dS(y) \\
&= \oint_{\partial B(0,1)} \nabla u(x + yr) \cdot y dS(y) \\
&= \oint_{\partial B(x,r)} \nabla u(y) \cdot \frac{y - x}{r} dS(y) \\
&= \oint_{\partial B(x,r)} \nabla u(y) \cdot \vec{n}_y dS(y) \\
(\text{Gauss-Green}) \quad &= \oint_{B(x,r)} \text{div}(\nabla u(y)) dS(y) \\
&= \oint_{B(x,r)} \underbrace{\Delta u(y)}_{\geq 0} dS(y) \geq 0
\end{aligned}$$

So we can conclude that

$$\oint_{\partial B(x,r)} u(y) dS(y) = f(r) \geq \lim_{r \rightarrow 0} f(r) = u(x).$$

Now regard

$$\begin{aligned}
\int_{B(x,r)} u(y) dy &= \int_0^r \left(\int_{\partial B(x,r)} u(y) dS(y) \right) ds \\
&= \int_0^r \left(|\partial B(x,r)| \oint_{\partial B(x,r)} u(y) dS(y) \right) ds \\
&\geq \int_0^r |\partial B(x,r)| \cdot u(x) dS(y) \\
&= u(x) \int_0^r |\partial B(x,r)| dS(y) = u(x) |B(x,r)|.
\end{aligned}$$

Thus we have

$$u(x) \leq \oint_{B(x,r)} u(y) dy.$$

Finally, lets regard

$$\begin{aligned}
\int_{B(x,r)} u(y) dy &= \int_0^r \left(|\partial B(x,s)| \oint_{\partial B(x,s)} u(y) dS(y) \right) ds \\
(\partial_r f(r) \geq 0) \quad &\leq \int_0^r \left(|\partial B(x,s)| \oint_{\partial B(x,r)} u(y) dS(y) \right) ds \\
&= \oint_{\partial B(x,r)} u(y) dS(y) \int_0^r |\partial B(x,s)| ds \\
&= \oint_{\partial B(x,r)} u(y) dS(y) \cdot |B(x,r)|
\end{aligned}$$

and we conclude

$$\oint_{B(x,r)} u(y) dy \leq \oint_{\partial B(x,r)} u(y) dS(y).$$

b) Let $x_0 \in \Omega$ s.t. $u(x_0) = \sup_{x \in \Omega} u(x)$. Now,

$$\begin{aligned} \sup_{x \in \Omega} u(x) = u(x_0) &\leq \oint_{\partial B(x_0,r)} u(y) dy \\ &\leq \oint_{\partial B(x_0,r)} \sup_{x \in \Omega} u(x) dy = \sup_{x \in \Omega} u(x) \end{aligned}$$

Since u is continuous we get $u(y) = u(x_0)$ for all $y \in B(x_0, r)$, so u is constant. ■

Definition 2.20 The *Poisson Equation* for given f, g on a bounded set is:

$$\begin{cases} -\Delta u = f, & \text{in } \Omega \\ u = g, & \text{on } \partial\Omega \end{cases}$$

Theorem 2.21 (Uniqueness) Let $\Omega \subseteq \mathbb{R}^d$ be bounded, open and connected. Let $f \in C(\Omega), g \in C(\partial\Omega)$. Then there exists *at most* one solution $u \in C^2(\Omega) \cap C(\bar{\Omega})$, s.t.

$$\begin{cases} -\Delta u = f, & \text{in } \Omega \\ u = g, & \text{on } \partial\Omega \end{cases}$$

Proof. Assume that we have two solutions u_1 and u_2 . Then $u := u_1 - u_2$ is a solution to

$$\begin{cases} -\Delta u = 0, & \text{in } \Omega \\ u = 0 & \text{on } \partial\Omega \end{cases}$$

By the maximum principle, we know that $u = 0$ in Ω . More precisely, by the maximum principle we have $\forall x \in \Omega$

$$\sup_{x \in \Omega} u(x) \leq \sup_{x \in \partial\Omega} u(x) = 0 \quad \Rightarrow \quad u(x) \leq 0$$

Since $-u$ satisfies the same property we have $\forall x \in \Omega$:

$$\sup_{x \in \Omega} (-u(x)) \leq \sup_{x \in \partial\Omega} (-u(x)) = 0 \quad \Rightarrow \quad -u(x) \leq 0 \quad \Rightarrow \quad u(x) \geq 0$$

So we get $u(x) = 0$ in Ω . ■

Exercise 2.22 (Bonus 1) Let Ω be open, connected and bounded in \mathbb{R}^d . Let $u \in C^2(\Omega) \cap C(\bar{\Omega})$ s.t.

$$\begin{cases} \Delta u = 0, & \text{in } \Omega \\ u = g, & \text{on } \partial\Omega \end{cases}$$

Prove that

a) If $g \geq 0$ on $\partial\Omega$, then $u \geq 0$ in Ω .

b) If $g \geq 0$ on $\partial\Omega$ and $g \neq 0$, then $u > 0$ in Ω .

Lemma 2.23 (Estimates for derivatives) If u is harmonic in $\Omega \subseteq \mathbb{R}^d$, $\alpha \in \mathbb{N}_0^d$, $|\alpha| = N$ and $B(x_0, r) \subseteq \Omega$, then

$$|D^\alpha u(x)| \leq \frac{(c_d N)^N}{r^{d+N}} \int_{B(x, r)} |u| dy$$

Proof. Induction: Assume $|\alpha| = N - 1$, Take $|\alpha| = N$

$$|D^\alpha u(x_0)| \leq \frac{|S_1|}{|B_1| \frac{r}{N}} \|D^\beta u\|_{L^\infty(B(x_0, \frac{r}{N}))}, \quad D^\alpha u = \partial_{x_i}(D^\beta u)_{|\beta|=N-1}$$

Note: $x \in B(x_0, \frac{r}{N})$, so $B(x, \frac{r(N-1)}{N}) \subseteq B(x_0, r)$. By the induction hypothesis:

$$\|D^\beta u\|_{L^\infty(B(x_0, \frac{r}{N}))} \leq \frac{[c_d(N-1)]^{N-1}}{[r \frac{(N-1)}{N}]^{d+N-1}} \int_{B(x_0, r)} |u| dy$$

The conclusion is:

$$\begin{aligned} |D^\alpha u(x_0)| &\leq \frac{|S_1|}{|B_1| \frac{r}{N}} \frac{[c_d(N-1)]^{N-1}}{(r \frac{N-1}{N})^{d+N-1}} \int_{B(x_0, r)} |u| dy \\ &= \frac{|S_1|}{|\beta_1|} \frac{c_d^{N-1}}{(\frac{r}{N})^{d+N} (N-1)^d} \int_{B(x_0, r)} |u| dy \\ &= \frac{|S_1|}{|\beta_1|} \frac{c_d^{N-1}}{(\frac{r}{N})^{d+N} N^d} \left(\frac{N}{N-1}\right)^d \int_{B(x_0, r)} |u| dy \\ &\leq \frac{2^d |S_1|}{|B_1|} \frac{c_d^{N-1} N^N}{r^{d+N}} \int_{B(x_0, r)} |u| dy \quad \text{if } c_d \geq \frac{2^d |S_1|}{|B_1|} \end{aligned}$$

■

Theorem 2.24 (Regularity) Let Ω be open in \mathbb{R}^d . Let $u \in C(\Omega)$ satisfy $u(x) = \int_{\partial B} u dy$ for any $x \in B(x, r) \subseteq \Omega$. Then u is a harmonic function in Ω . Moreover, $u \in C^\infty(\Omega)$ and u is analytic in Ω .

Exercise 2.25 (E 1.1: Proof the Gauss–Green formula) Let $f := (f_i)_1^d \in C^1(\mathbb{R}^d, \mathbb{R}^d)$. Prove that for every open ball $B(y, r) \subseteq \mathbb{R}^d$ we have

$$\int_{\partial B(y, r)} f(y) \cdot \nu_y dS(y) = \int_{B(y, r)} \operatorname{div} f dx.$$

Here ν_y is the outward unit normal vector and dS is the surface measure on the sphere.

Solution. We proof this in $d=3$. Let $f \in C^1(\mathbb{R}^3)$

$$\int_{B(0,1)} \partial_{x_3} f dx = \int_{\partial B(0,1)} f x_3 dS(x), \quad x = (x_1, x_2, x_3) \in \mathbb{R}^3, \vec{n} = \frac{x}{|x|} \text{ on } \partial B(0,1)$$

$$\begin{aligned} B(0,1) &= \{x_1^2 + x_2^2 + x_3^2 \leq 1\} \\ &= \{x_1^2 + x_2^2 \leq 1 - \sqrt{1 - x_1^2 - x_2^2} \leq x_3 \leq \sqrt{1 - x_1^2 - x_2^2}\} \end{aligned}$$

Then:

$$\begin{aligned}\int_{B(0,1)} \partial_{x_3} f \, dx &= \int_{x_1^2 + x_2^2 \leq 1} \left(\int_{-\sqrt{1-x_1^2-x_2^2} \leq x_3 \leq \sqrt{1-x_1^2-x_2^2}} \partial_{x_3} f \, dx_3 \right) dx_1 \, dx_2 \\ &= \int_{x_1^2 + x_2^2 \leq 1} \left[f(x_1, x_2, \sqrt{1-x_1^2-x_2^2}) \right. \\ &\quad \left. - f(x_1, x_2, -\sqrt{1-x_1^2-x_2^2}) \right] dx_1 \, dx_2\end{aligned}$$

Lets take polar coordinates in 2D:

$$\begin{aligned}x_1 &= r \cos \phi & r > 0, \phi \in [0, 2\pi) \\ x_2 &= r \sin \phi & \det \frac{\partial(x_1, x_2)}{\partial(r, \phi)} = r\end{aligned}$$

$$(\star) = \int_0^1 \int_0^{2\pi} [f(r \cos \phi, r \sin \phi, r) - f(r \cos \phi, r \sin \phi, -r)] r \, dr \, d\phi$$

On the other hand:

$$\int_{\partial B(0,1)} f x_3 \, dS$$

The polar coordinates in 3D are:

$$\begin{aligned}x_1 &= r \cos \phi \sin \theta & r > 0, \phi \in (0, 2\pi), \theta \in (0, \pi) \\ x_2 &= r \sin \phi \sin \theta & \det \frac{\partial(x_1, x_2, x_3)}{\partial(r, \phi, \theta)} = r^2 \sin \theta \\ x_3 &= r \cos \theta\end{aligned}$$

Then:

$$\begin{aligned}(\star\star) &= \int_0^{2\pi} \int_0^\pi f(\cos \phi \sin \theta, \sin \phi \sin \theta, \cos \theta) \sin \theta \cos \theta \, d\theta \, d\phi \\ &= \int_0^{2\pi} \left(\int_0^{\frac{\pi}{2}} + \int_{\frac{\pi}{2}}^\pi d\theta \right) d\phi \\ (r = \sin \theta) \quad &= \int_0^{2\pi} \int_0^1 f(r \cos \phi, r \sin \phi, \sqrt{1-r^2}) r \, dr \, d\phi \\ &\quad - \int_0^{2\pi} \int_0^1 f(r \cos \phi, r \sin \phi, -\sqrt{1-r^2}) r \, dr \, d\phi \quad \blacksquare\end{aligned}$$

Exercise 2.26 (E 1.2) Let $u \in C(\mathbb{R}^d)$ and $\int_{B(x,r)} u \, dy = 0$ for every open ball $B(x,r) \subseteq \mathbb{R}^d$. Show that $u(x) = 0$ for all $x \in \mathbb{R}^d$.

My Solution. Assume there is a $x_0 \in \mathbb{R}^d$ s.t. w.l.o.g. $u(x_0) > 0$. Since u is continous there is a ball $B(x_0, r)$ s.t. $u(y) > \frac{u(x_0)}{2}$ for all $y \in B(x_0, r)$. But then we get

$$\int_{B(x_0, r)} u(y) \, dy \geq \int_{B(x_0, r)} \frac{u(x_0)}{2} \, dy = \frac{u(x_0)}{2} |B(x_0, r)| > 0. \quad \blacksquare$$

Exercise 2.27 (E 1.3) Let $f \in C_c^1(\mathbb{R}^d)$ with $d \geq 2$ and $u(x) := (\Phi \star f)(x)$. Prove that $u \in C^2(\mathbb{R}^2)$ and $-\Delta u(x) = f(x)$ for all $x \in \mathbb{R}^d$ (2.9 was the same for $f \in C_1(\mathbb{R})$)

Theorem 2.28 (Liouville's Theorem) If $u \in C^2(\mathbb{R}^d)$ is harmonic and bounded, then $u = \text{const.}$

Proof. By the bound of the derivative 2.23 we have

$$\begin{aligned} |\partial_{x_i} u(x_0)| &\leq \frac{c_d}{r^{d+1}} \int_{B(x_0, r)} |u| dy \quad \forall x_0 \in \mathbb{R}^d \quad \forall r > 0 \\ &\leq \|u\|_{L^\infty} \frac{c_d}{r^{d+1}} |B(x_0, r)| \\ &\leq \|u\|_{L^\infty} \frac{c_d}{r} \xrightarrow{r \rightarrow \infty} 0 \end{aligned}$$

Thus $\partial_{x_i} u = 0$ for all $i = 1, 2, \dots, d$ and $u = \text{const.}$ in \mathbb{R}^d ■

Theorem 2.29 (Uniqueness of solutions to Poisson Equation in \mathbb{R}^d) If $u \in C^2(\mathbb{R}^d)$ is a bounded function and satisfies $-\Delta u = f$ in \mathbb{R}^d where $f \in C_c^2(\mathbb{R}^d)$, then we have

$$u(x) = \Phi \star f(x) + C = \int_{\mathbb{R}^d} \Phi(x-y) f(y) dy + C \quad \forall x \in \mathbb{R}^d$$

where C is a constant and Φ is the fundamental solution of the Laplace equation in \mathbb{R}^d .

Proof. If we can prove that v is bounded, then $v = \text{const.}$ We first need to show that $\Phi \star f$ is bounded.

$$\begin{aligned} \Phi &= \Phi_1 + \Phi_2 = \Phi \mathbb{1}(|x| \leq 1) + \Phi(|x| \geq 1) \\ \Phi \star f &= \Phi_1 \star f + \Phi_2 \star f \end{aligned}$$

We have $\Phi_1 \star f \in L^1(\mathbb{R}^d)$ and $\Phi_2 \star f$ is bounded since $\Phi \rightarrow 0$ as $|x| \rightarrow \infty$ in $d \geq 3$. ■

Exercise 2.30 (Hanack's inequality) Let $u \in C^2(\mathbb{R}^d)$ be harmonic and non-negative. Prove that for all open, bounded and connected $\Omega \subseteq \mathbb{R}^d$, we have

$$\sup_{x \in \Omega} u(x) \leq C_\Omega \inf_{x \in \Omega} u(x),$$

where C_Ω is a finite constant depending only on Ω .

Proof. (Exercise) Hint: $\Omega = B(x, r)$. General case cover Ω by finitely many balls, one ball is inside Ω . ■

Chapter 3

Convolution, Fourier Transform and Distributions

3.1 Convolutions

Definition 3.1 (Convolution) Let $f, g : \mathbb{R}^d \rightarrow \mathbb{R}$ or \mathbb{C} .

$$(f \star g)(x) = \int_{\mathbb{R}^d} f(x-y)g(y) dy = \int_{\mathbb{R}^d} f(y)g(x-y) dy = (g \star f)(x)$$

Remark 3.2 (Properties of the Convolution)

- $(f \star g)(x) = f \star (g \star h)$
- $\widehat{f \star g} = \hat{f} \star \hat{g}$

Theorem 3.3 (Young Inequality) If $f \in L^1(\mathbb{R}^d)$ and $g \in L^p(\mathbb{R}^d)$, where $1 \leq p \leq \infty$, then $f \star g \in L^p(\mathbb{R}^d)$ and

$$\|f \star g\|_{L^p} \leq \|f\|_{L^1} \|g\|_{L^p}.$$

More generally, if $f \in L^p(\mathbb{R}^d)$, $g \in L^q(\mathbb{R}^d)$, then $f \star g \in L^r(\mathbb{R}^d)$,

$$\|f \star g\|_{L^r} \leq \|f\|_{L^p} \|g\|_{L^q},$$

where $1 \leq p, q, r \leq \infty$, $\frac{1}{p} + \frac{1}{q} = 1 + \frac{1}{r}$.

Proof. Let $f \in L^1, g \in L^p$. With the Hölder Inequality we have:

$$\begin{aligned} |(f \star g)(x)| &= \left| \int_{\mathbb{R}^d} f(x-y)g(y) dy \right| \\ &\leq \left(\int_{\mathbb{R}^d} |f(x-y)| dy \right)^{\frac{1}{q}} \left(\int_{\mathbb{R}^d} |f(x-y)||g(y)|^p dy \right)^{\frac{1}{p}} \\ &= \|f\|_{L^1}^{\frac{1}{q}} \left(\int_{\mathbb{R}^d} |f(x-y)||g(y)|^p dy \right)^{\frac{1}{p}} \\ \|f \star g\|_{L^p}^p &= \int_{\mathbb{R}^d} |f \star g(x)|^p dx \\ &\leq \|f\|_{L^1}^{\frac{p}{q}} \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} |f(x-y)||g(y)|^p dy dx \\ &= \|f\|_{L^1}^{\frac{p}{q}+1} \|g\|_{L^p}^p \end{aligned}$$

So we have $\|f \star g\|_{L^p} \leq \|f\|_{L^1} \|g\|_{L^p}$ ■

Theorem 3.4 (Smoothness of the Convolution) If $f \in C_c^\infty(\mathbb{R}^d)$, $g \in L^p(\mathbb{R}^d)$, $1 \leq p \leq \infty$. Then $f \star g \in C^\infty(\mathbb{R})$ and

$$D^\alpha(f \star g) = (D^\alpha f) \star g$$

for all $\alpha = (\alpha_1, \dots, \alpha_d)$, $\alpha_i \in \{0, 1, 2, \dots\}$

Proof. First we note that $x \mapsto (f \star g)$ is continuous as $x_n \rightarrow x$ in \mathbb{R}^d since

$$(f \star g)(x_n) = \int_{\mathbb{R}^d} f(x_n - y)g(y) dy \xrightarrow{\text{dom. conv.}} \int_{\mathbb{R}^d} f(x - y)g(y) dy = (f \star g)(x)$$

We can apply Dominated convergence because

$$f(x_n - y)g(y) \rightarrow f(x - y)g(y) \quad \forall y \text{ as } f \text{ is continuous and } x_n \rightarrow x$$

and

$$|f(x_n - y)g(y)| \leq \|f\|_{L^\infty} |g(y)| \mathbb{1}(|y| \leq R) \in L^1(\mathbb{R}^d).$$

Where $R > 0$ satisfies $B(0, R) \supseteq \text{supp } f + \sup_n |x_n|$. Now we can compute the derivatives:

$$\begin{aligned} \partial_{x_i}(f \star g)(x) &= \lim_{h \rightarrow 0} \frac{(f \star g)(x + he_i) - (f \star g)(x)}{h} \\ &= \lim_{h \rightarrow 0} \int_{\mathbb{R}^d} \frac{f(x + he_i - y) - f(x - y)}{h} g(y) dy \\ (\text{Dominated Convergence}) \quad &= \int_{\mathbb{R}^d} \lim_{h \rightarrow 0} \frac{f(x + he_i - y) - f(x - y)}{h} g(y) dy \\ &= \int_{\mathbb{R}^d} (\partial_{x_i} f)(x - y)g(y) dy \end{aligned}$$

We could apply Dominated Convergence since

$$\begin{aligned} \frac{f(x + he_i - y) - f(x - y)}{h} g(y) &\xrightarrow{h \rightarrow 0} (\partial_{x_i} f)(x - y)g(y) \quad \text{as } f \in C^1 \\ \left| \frac{f(x + he_i - y) - f(x - y)}{h} g(y) \right| &\leq \|\partial_{x_i} f\|_{L^\infty} |g(y)| \mathbb{1}(|y| \leq R) \in L^1(\mathbb{R}^d) \end{aligned}$$

where $B(0, R) \supseteq \text{supp}(f) + B(0, |x| + 1)$ and $\partial_{x_i}(f \star g) = (\partial_{x_i} f) \star g \in C(\mathbb{R}^d)$ since $\partial_{x_i} f \in C_c^\infty(\mathbb{R}^d)$. By induction we get $D^\alpha(f \star g) = (D^\alpha f \star g) \in C(\mathbb{R}^d)$. ■

Remark 3.5 Question: Is there a f s.t. $f \star g = g$ for all g ? In fact there is no regular function f that solves this formally:

$$f \star g = g \Rightarrow \widehat{f \star g} = \hat{g} \Rightarrow \hat{f} \hat{g} = \hat{g} \Rightarrow \hat{f} = 1 \Rightarrow f \text{ is not a regular function!}$$

However, if f is the Dirac-Delta Distribution, $f = \delta_0$ then $\delta_0 \star g = g$ for all g . Formally:

$$\delta_0(x) = \begin{cases} 0 & x \neq 0 \\ \infty & x = 0 \\ \int \delta_0 = 1 \end{cases}$$

In fact, if $f \in L^1(\mathbb{R}^d)$, $\int f = 1$, $f_\epsilon(x) = \epsilon^{-d} f(\epsilon^{-1}x)$, then $f_\epsilon \rightarrow \delta_0$ in an appropriate sense and $f_\epsilon \star g \rightarrow g$ for all g nice enough.

Theorem 3.6 (Approximation by convolution) Let $f \in L^1(\mathbb{R}^d)$, $\int f = 1$, $f_\epsilon(x) = \epsilon^{-d} f(\frac{x}{\epsilon})$. Then for all $g \in L^p(\mathbb{R}^d)$, where $1 \leq p < \infty$, then

$$f_\epsilon \star g \rightarrow g \quad \text{in } L^p(\mathbb{R}^d)$$

Proof.

Step 1: Let $f, g \in C_c(\mathbb{R}^d)$. Then

$$\begin{aligned} (f_\epsilon \star g)(x) - g(x) &= \int_{\mathbb{R}^d} f_\epsilon(y)g(x-y) dy - g(x) \int_{\mathbb{R}^d} f_\epsilon(y) dy \\ &= \int_{\mathbb{R}^d} f_\epsilon(y)g(x-y) dy - \int_{\mathbb{R}^d} f_\epsilon(y)g(x) dy \\ &= \int_{\mathbb{R}^d} f_\epsilon(y)(g(x-y) - g(x)) dy \\ |(f_\epsilon \star g)(x) - g(x)| &= \left| \int_{\mathbb{R}^d} f_\epsilon(y)(g(x-y) - g(x)) dy \right| \\ &\leq \int_{\mathbb{R}^d} |f_\epsilon(y)| |g(x-y) - g(x)| dy \\ &\leq \int_{|y| \leq R_\epsilon} |f_\epsilon(y)| |g(x-y) - g(x)| dy \\ &\leq \left[\sup_{|z| \leq R} |g(x-z) - g(x)| \right] \underbrace{\int_{|y| \leq R_\epsilon} |f_\epsilon(y)| dy}_{\leq \|f_\epsilon\|_{L^1} = \|f\|_{L^1}} \xrightarrow{\epsilon \rightarrow 0} 0 \end{aligned}$$

We have Dominated Convergence since:

$$(f_\epsilon \star g)(x) - g(x) \rightarrow 0 \quad \text{as } \epsilon \rightarrow 0$$

and

$$|f_\epsilon \star g(x) - g(x)| \leq \|f\|_{L^1} \sup_{|z| \leq R_\epsilon} |g(x-z) - g(x)| \leq 2\|f\|_1 \|g\|_{L^\infty} \mathbb{1}(|x| \leq R_1).$$

Where $B(0, R_1) \supseteq \text{supp}(g) + B(0, R_\epsilon)$, thus $f_\epsilon \star g \rightarrow g$ in $L^p(\mathbb{R}^d)$. To remove the technical assumptions $f, g \in C_c(\mathbb{R}^d)$, then we use a density argument. We use the fact that $C_c(\mathbb{R}^d)$ is dense in $L^p(\mathbb{R}^d)$, $1 \leq p < \infty$.

Step 2: Let $g \in C_c(\mathbb{R}^d)$, $g \in L^p(\mathbb{R}^d)$. Then there is $\{g_m\} \subseteq L^p(\mathbb{R}^d)$, $g_m \rightarrow g$ in $L^p(\mathbb{R}^d)$. Then

$$\begin{aligned} \|f_\epsilon \star g - g\|_{L^p} &\leq \|f_\epsilon \star (g - g_m)\|_{L^p} + \|f_\epsilon \star g_m - g_m\|_{L^p} + \|g_m - g\|_{L^p} \\ (\text{Young}) &\leq \|f_\epsilon\|_{L^1} \|g - g_m\|_{L^p} + \|f_\epsilon \star g_m - g_m\|_{L^p} + \|g_m - g\|_{L^p} \\ &\leq \|f\|_{L^1} \|g - g_m\|_{L^p} + \|f_\epsilon \star g_m - g_m\|_{L^p} + \|g_m - g\|_{L^p} \\ &\leq (\|f\|_{L^1} + 1) \|g - g_m\|_{L^p} + \|f \star g_m - g_m\|_{L^p} \end{aligned}$$

So we get:

$$\begin{aligned} \limsup_{\epsilon \rightarrow 0} \|f_\epsilon \star g - g\|_{L^p} &\leq (\|f\|_{L^p} + 1) \|g - g_m\|_{L^p} + \underbrace{\limsup_{\epsilon \rightarrow 0} \|f_\epsilon \star g_m - g_m\|_{L^p}}_{0 \text{ by step 1.}} \xrightarrow{m \rightarrow \infty} 0. \end{aligned}$$

Step 3: Let $f \in L^1(\mathbb{R}^d)$ and $g \in L^p(\mathbb{R}^d)$. Take $\{f_m\} \subseteq C_c(\mathbb{R}^d)$, s.t.

$$\begin{cases} F_m \rightarrow g \in L^1(\mathbb{R}) \text{ as } m \rightarrow \infty \\ \int_{\mathbb{R}^d} F_m = 1 \text{ (it is possible since } \int_{\mathbb{R}^d} f = 1) \end{cases}$$

Define $F_{m,\epsilon}(x) = \epsilon^{-d} F_m(\epsilon^{-1}x)$ (recall $f_\epsilon(x) = \epsilon^{-d} f(\epsilon^{-1}x)$). Then:

$$\begin{aligned} f_\epsilon \star g - g &= (f_\epsilon - F_{m,\epsilon}) \star g + F_{m,\epsilon} \star g - g \\ \Rightarrow \|f_\epsilon - g\|_{L^p} &\leq \underbrace{\|f_\epsilon - F_{m,\epsilon} \star g\|_{L^p}}_{\substack{\text{Young} \\ \leq \|f_\epsilon - F_{m,\epsilon}\|_{L^1} \|g\|_{L^p} = \|f - F_m\|_{L^1} \|g\|_{L^p}}} + \|F_{m,\epsilon} \star g - g\|_{L^p} \\ \Rightarrow \limsup_{\epsilon \rightarrow 0} \|f_\epsilon \star g - g\|_{L^p} &\leq \|f - F_m\|_{L^1} \|g\|_{L^p} = \|f - F_m\|_{L^1} \|g\|_{L^p} \quad \blacksquare \end{aligned}$$

Lemma 3.7 $C_c(\mathbb{R}^d)$ is dense in $L^p(\mathbb{R}^d)$, $1 \leq p < \infty$

Proof. For all $g \in L^p(\mathbb{R}^d)$ there are step functions $(g_m)_m$ and $g_m \rightarrow g$ in $L^p(\mathbb{R}^d)$,

$$g_m(x) = \sum_{\substack{\Omega \\ \text{finite sum} \\ \Omega \subseteq \mathbb{R}^d \text{ measurable}}} \chi_\Omega(x) a_\Omega.$$

We can assume that Ω is open and bounded and we want to approximate χ_Ω by $C_c(\mathbb{R}^d)$. \blacksquare

Lemma 3.8 (Urnson) Define

$$\Omega_\epsilon = \{x \in \Omega \mid \text{dist}(x, \partial\Omega) > \epsilon\}$$

Then there is a $\eta_\epsilon \in C_c(\mathbb{R}^d)$ s.t.

$$\begin{cases} 0 \leq \eta(x) \leq 1 & \forall x \in \mathbb{R}^d \\ \eta_\epsilon(x) = 1 & \text{if } x \in \Omega_\epsilon \\ \eta_\epsilon(x) = 0 & \text{if } x \notin \Omega \end{cases}$$

Lemma 3.9 (General Version of Urnson) If $A, B \subseteq \mathbb{R}^d$, A closed, B closed, $A \cap B = \emptyset$. Then

$$\eta(x) = \frac{\text{dist}(x, A)}{\text{dist}(x, A) + \text{dist}(x, B)}$$

Then $\eta \in C(\mathbb{R}^d)$, $0 \leq \eta \leq 1$ and $\eta = 0$ if $x \in B$, $\eta = 1$ if $x \in A$.

For example, this lemma can be applied to $A = \overline{\Omega_\epsilon} \subsetneq \Omega$ and $B = \mathbb{R}^d \setminus \Omega$ for $\Omega \subseteq \mathbb{R}^d$ open.

Theorem 3.10 (Appendix C4 in Evans) Let Ω be open in \mathbb{R}^d and for $\epsilon > 0$ define

$$\Omega_\epsilon = \{x \in \Omega \mid \text{dist}(x, \mathbb{R}^d \setminus \Omega) > \epsilon\}$$

Let $f \in C_c^\infty(\mathbb{R}^d)$, $\int_{\mathbb{R}^d} f = 1$, $\text{supp } f \subseteq B(0, 1)$, $f_\epsilon(x) = \epsilon^{-d} f(\epsilon^{-1}x)$. Then $\text{supp } f_\epsilon \subseteq B(0, \epsilon)$ and for all $g \in L_{loc}^p(\Omega)$ (i.e. $\mathbf{1}_K g \in L^p(\Omega)$ for all $K \subseteq \Omega$ compact) we have

- a) $g_\epsilon(x) = (f_\epsilon \star g)(x) = \int_{\mathbb{R}^d} f_\epsilon(x-y)g(y) dy - \int_{\Omega} f_\epsilon(x-y)g(y) dy$ is well-defined in Ω_ϵ and $g_\epsilon \in C^\infty(\Omega_\epsilon)$,

- b) $g_\epsilon \rightarrow g$ in $L^p_{loc}(\Omega)$ if $1 \leq p < \infty$ and $g_\epsilon(x) \rightarrow g(x)$ almost everywhere $x \in \Omega$,
c) If $g \in C(\Omega)$, then $g_\epsilon(x) \rightarrow g(x)$ uniformly in any compact subset of Ω .

Proof. a) $D^\alpha(g_\epsilon) = (D^\alpha f_\epsilon) \star g \in C(\Omega_\epsilon)$

- b) Already proved in \mathbb{R}^d space. ■

Corrolary 3.11 (Lebesgue differentiation theorem) If $f \in L^p_{loc}(\mathbb{R}^d)$, then

$$\int_{B(x,\epsilon)} |f(y) - f(x)|^p dy \rightarrow 0 \quad \text{as } \epsilon \rightarrow 0$$

Exercise 3.12 (E 2.1) Let $u \in C^2(\mathbb{R}^2)$ be convex, i.e.

$$tu(x) + u(y)(1-t) \geq u(tx + (1-t)y)$$

for all $x, y \in \mathbb{R}^d$, $t \in [0, 1]$.

- a) Prove for all $x \in \mathbb{R}^d$ that the Hessian matrix H is positive semidefinite.
b) Prove that u is sub-harmonic in \mathbb{R}^d .

Solution.

- a) In 1D: If u is convex $\Leftrightarrow u''(x) \geq 0$ for all $x \in \mathbb{R}$. In general: Taylor expansion for all $x, z \in \mathbb{R}^d$:

$$cu(x) = u(z) + \nabla u(z)(x-z) + \int_0^1 \sum_{|\alpha|=2} D^\alpha u(z + s(x-z)) \frac{(x-z)^\alpha}{\alpha!} ds$$

Note that we have $x = z + s(x-z)$ if $s = 1$. Use $z = tx + (1-t)y \Rightarrow x - z = (1-t)(x-y)$

$$tu(x) = tu(z) + t\nabla u(z)(1-t)(x-y) + t \int_0^1 \sum_{|\alpha|=2} D^\alpha u(z + s(x-z)) \frac{[(1-t)(x-y)]^\alpha}{\alpha!} ds$$

$$(1-t)u(y) = (1-t)u(z) + (1-t)\nabla u(z)t(y-x) + (1-t) \int_0^1 \sum_{|\alpha|=2} D^\alpha u(z + s(y-z)) \frac{[t(y-x)]^\alpha}{\alpha!} ds$$

$$\Rightarrow tu(x) + (1-t)u(y) = u(z) + t \int_0^1 \dots + (1-t) \int_0^1 \dots$$

$$\Rightarrow t \int_0^1 \dots + (1-t) \int_0^1 \dots \geq 0 \forall x, y, t, z = tx + (1-t)y$$

$$t(1-t)^2 \int_0^1 \sum_{|\alpha|=2} D^\alpha u(z + s(x-z)) \frac{(x-y)^\alpha}{\alpha!} ds + (1-t)t^2 \int_0^1 \sum_{|\alpha|=2} D^\alpha u(z + s(y-z)) \frac{(y-x)^\alpha}{\alpha!} ds \geq 0$$

for all $x, y \in \mathbb{R}^d$, $t \in [0, 1]$, $z = tx + (1-t)y$. Divides for $t(1-t)$

$$(1-t) \int_0^1 \dots + \int_0^1 \dots \geq 0$$

Take $t \rightarrow 0$

$$\int_0^1 \sum_{|\alpha|=2} D^\alpha u(y + s(x-y)) \frac{(x-y)^\alpha}{\alpha!} ds \geq 0 \forall x, y \in \mathbb{R}^d$$

Take $y = x + a, a \in \mathbb{R}^d$

$$\int_0^1 \sum_{|\alpha|=2} D^\alpha u(x + a + sa) \frac{a^\alpha}{\alpha!} ds \geq 0 \forall \epsilon > 0, \forall x, a \in \mathbb{R}^d$$

Take $\epsilon \rightarrow 0$

$$\int_0^1 \sum_{|\alpha|=2} D^\alpha u(x) \frac{a^\alpha}{\alpha!} \geq 0 \Rightarrow \sum_{i,j=1, i \neq j} \partial_{x_i} \partial_{x_j} u(x) a_i a_j + \sum_{i=1}^d \partial_{x_i}^2 u(x) \frac{a_i^2}{2}$$

We get

$$\frac{1}{2} a^T H a \geq 0 \forall a(a_i)_{i=1}^d \in \mathbb{R}^d$$

$$\text{b) } H(x) \geq 0 \Rightarrow (\partial_i \partial_j u) \geq 0 \Rightarrow \text{Tr} H(x) \geq 0 \Rightarrow \sum_{i=1}^d \partial_{x_i}^2 u(x) \geq 0 \Rightarrow \Delta u(x) \geq 0 \forall x \in \mathbb{R}^d$$

■

Exercise 3.13 (E 2.2, Newton's Theorem) Let $d \geq 3$.

a) Prove that for all $r > 0$ and $x \in \mathbb{R}^d$, we have

$$\oint_{\partial B(x,r)} \frac{dS(y)}{|y|^{d-2}} = \frac{1}{\max(|x|, r)^{d-2}}$$

where $dS(y)$ is the surface measure on the sphere $\partial B(x, r) \subseteq \mathbb{R}^d$.

b) Let $0 \leq f_1, f_2 \in L^1(\mathbb{R}^d)$ be radial functions with $\int_{\mathbb{R}^d} f_i = M_i$. Prove that for all $z_1, z_2 \in \mathbb{R}^d$ we have

$$\int \int_{\mathbb{R}^d} \frac{f_1(x - z_1) f_2(y - z_2)}{|x - y|^{d-2}} dx dy \leq \frac{M_1 M_2}{|z_1 - z_2|^{d-2}}$$

Moreover, prove that we have the equality if f_1, f_2 are compactly supported and $|z_1 - z_2|$ is sufficiently large.

Hint: For a) you may use the mean-value theorem (the function $\frac{1}{|x|^{d-2}}$ is harmonic in Ω if $0 \notin \Omega$). For b) you may use a) and polar coordinates.

Solution. a) Regard $d = 3$. The function $\frac{1}{|x|}$ is harmonic in $\mathbb{R}^3 \setminus \{0\}$. We prove

$$\oint_{\partial B(x,r)} \frac{dS(y)}{|y|} = \frac{1}{\max(|x|, r)}$$

If $|x| > r$, then $0 \notin B(x, r + \epsilon)$. Then

$$y \mapsto \frac{1}{|y|}$$

is harmonic in $B(x, r + \epsilon)$. Then by the Mean Value Property:

$$\oint_{\partial B(x, r)} \frac{dS(y)}{|y|} = \frac{1}{|x|}$$

If $|x| < r$: Then $\frac{1}{|y|}$ is not harmonic in $B(x, r)$ since $0 \in B(x, r)$. Note

$$\oint_{\partial B(x, r)} \frac{dS(y)}{|y|} = \oint_{\partial B(0, r)} \frac{dS(y)}{|x - y|}$$

This function depends on x only via $|x|$.

$$\dots = \oint_{\partial B(0, r)} \frac{dS(y)}{|Rx - Ry|}$$

for all R rotation $SO(3)$, $dS(Ry) = dS(y)$

$$\begin{aligned} &= \oint_{\partial B(0, r)} \frac{dS(y)}{|Rx - y|} \\ &= \oint_{\partial B(0, r)} \frac{dS(y)}{|z - y|} \\ \text{(Radial in } z) \quad &= \oint_{\partial B(0, |x|)} \left(\oint_{\partial B(0, r)} \frac{dS(y)}{|z - y|} \right) dS(z) \\ \text{(Fubini)} \quad &= \oint_{\partial B(0, r)} \left(\oint_{\partial B(0, |x|)} \frac{dS(z)}{|z - y|} \right) dS(y) \\ \text{(case 1 since } |y| = r > |x|) \quad &= \oint_{\partial B(0, r)} \frac{1}{|y|} dS(y) = \frac{1}{r} \end{aligned}$$

If $|x| = r$: Continuity: $x \mapsto \oint_{\partial B(0, r)} \frac{dS(y)}{|x - y|}$

b)

Remark 3.14 For $f \in C^{|\alpha|}, g \in C^{|\beta|}$:

$$D^{\alpha+\beta}(f \star g) = (D^\alpha f) \star (D^\beta g)$$

Lemma 3.15 If $d \geq 3$ and $f : \mathbb{R}^d \rightarrow \mathbb{R}$ radial. Then:

$$\left(\frac{1}{|x|^{d-2}} \star f \right) (x) = \int_{\mathbb{R}^d} \frac{f(y)}{|x - y|^{d-2}} dy = \int_{\mathbb{R}^d} \frac{f(y)}{\max(|x|^{d-2}, |y|^{d-2})} dy$$

Proof. (d=3) Polar coordinates:

$$\begin{aligned} \int_{\mathbb{R}^3} \frac{f(y)}{|x - y|} dy &= \int_0^\infty \left[\int_{\partial B(0, 1)} \frac{d\omega}{|x - rw|} \right] f(r) dr \\ (a) \quad &= \int_0^\infty \left[\int_{\partial B(0, 1)} \frac{d\omega}{\max(|x|, r)} \right] f(r) dr \\ &= \int_{\mathbb{R}^3} \frac{f(y)}{\max(|x|, |y|)} dy \end{aligned}$$

■

Now, for $d = 3$, if f radial and non-negative with the lemma we get

$$(\star) \quad \int_{\mathbb{R}^3} \frac{f(y)}{|x-y|} dy = \int_{\mathbb{R}^3} \frac{f(y)}{\max(|x|, |y|)} dy \leq \int_{\mathbb{R}^3} \frac{f(y)}{|x|} dy = \frac{(\int_{\mathbb{R}^3} f(y) dy)}{|x|}$$

Then

$$\begin{aligned} \int_{\mathbb{R}^3} \int_{\mathbb{R}^3} \frac{f_1(x-z_1)f_2(y-z_2)}{|x-y|} dx dy &= \int_{\mathbb{R}^3} \int_{\mathbb{R}^3} \frac{f_1(x)f_2(y)}{|x+z_1-y-z_2|} dx dy \\ &= \int_{\mathbb{R}^3} \left(\int_{\mathbb{R}^3} \frac{f_1(x)}{|x+z_1-y-z_2|} dx \right) f_2(y) dy \\ (\star) \quad &\leq \int_{\mathbb{R}^3} \frac{(\int_{\mathbb{R}^3} f_1(x) dx) f_2(y)}{|y+z_2-z_1|} dy \\ &\leq \frac{(\int_{\mathbb{R}^3} f_1)(\int_{\mathbb{R}^3} f_2)}{|z_1-z_2|} \quad \blacksquare \end{aligned}$$

Exercise 3.16 (Bonus 2) a) Prove that $u(x) = \frac{1}{|x|}$ is sub-harmonic in $\mathbb{R}^2 \setminus \{0\}$.

b) Prove that if $f : \mathbb{R}^2 \rightarrow \mathbb{R}$ radial, non-negative, measurable:

$$\int_{\mathbb{R}^2} \frac{f(y)}{|x-y|} dy \geq \int_{\mathbb{R}^2} \frac{f(y)}{\max(|x|, |y|)} dy$$

3.2 Fourier Transformation

Definition 3.17 (Fourier Transform) For $f \in L^1(\mathbb{R}^d)$ define

$$\mathcal{F}f(k) = \hat{f}(k) = \int_{\mathbb{R}^d} f(x) e^{-2\pi i k \cdot x} dx, \quad k \cdot x = \sum_{i=1}^d k_i x_i$$

Theorem 3.18 (Basic Properties) 1. If $f \in L^1(\mathbb{R}^d)$, then $\hat{f} \in L^\infty(\mathbb{R}^d)$ and $\|\hat{f}\|_{L^\infty} \leq \|f\|_{L^1}$

2. For all $f \in L^1(\mathbb{R}^d) \cap L^2(\mathbb{R}^d)$, $\|\hat{f}\|_{L^2} = \|f\|_{L^2}$. Moreover, \mathcal{F} can be extended to be a unitary transform $L^2(\mathbb{R}^d) \rightarrow L^2(\mathbb{R}^d)$ s.t.

$$\|\mathcal{F}g\|_{L^2} = \|g\|_{L^2} \quad \forall g \in L^2(\mathbb{R}^d)$$

3. The inverse of \mathcal{F} can be defined as

$$(F^{-1}f)(x) = \check{f}(x) = \int_{\mathbb{R}^d} f(x) e^{2\pi i k x} dk$$

for all $f \in L^1(\mathbb{R}^d) \cap L^2(\mathbb{R}^d)$

4. $\widehat{D^\alpha f}(k) = (2\pi i k)^\alpha \hat{f}(k)$ as $(2\pi i k)^\alpha f(k) \in L^2(\mathbb{R}^d)$ ($k^\alpha = k_1^{\alpha_1} \dots k_n^{\alpha_n}$)

5. $\widehat{f \star g}(k) = \hat{f}(k)\hat{g}(k)$ if f, g are nice enough.

Theorem 3.19 (Hausdorff-Young-Inequality) If $1 \leq p \leq 2$, $\frac{1}{p} + \frac{1}{p'} = 1$ and $f \in L^p(\mathbb{R}^d) \cap L^1(\mathbb{R}^n)$ then

$$\|\hat{f}\|_{L^{p'}} \leq \|f\|_{L^p}$$

and

$$\|\hat{f}\|_{L^p} \leq \|f\|_{L^{p'}} \quad \forall f \in L^p(\mathbb{R}^d)$$

Remark 3.20 We want to apply the Fourier transform to find the solution of a PDE, e.g. the Poisson-Equation:

$$-\Delta u = f \text{ in } \mathbb{R}^d \Rightarrow |2\pi k|^2 \hat{u}(k) = \hat{f}(k) \Rightarrow \hat{u}(k) = \frac{1}{|2\pi k|^2} \hat{f}(k)$$

If we can find G s.t. $\hat{G}(k) = \frac{1}{|2\pi k|^2}$, then

$$\begin{aligned} \hat{u}(k) &= \hat{G}(k) \hat{f}(k) = \widehat{G \star f} \\ \Rightarrow u(x) &= (G \star f)(x) = \int_{\mathbb{R}^d} G(x-y) f(y) dy \end{aligned}$$

In fact G is the fundamental solution of laplace quation.

Theorem 3.21 (Fourier Transform of $\frac{1}{|x|^\alpha}$ for $0 < \alpha < d$) We have formally

$$\widehat{\frac{c_\alpha}{|x|^\alpha}} = \frac{c_{d-\alpha}}{|k|^{d-\alpha}} \quad \forall 0 < \alpha < d$$

Here

$$c_\alpha = \pi^{-\frac{d}{2}} \Gamma\left(\frac{\alpha}{2}\right) = \pi^{-\frac{\alpha}{2}} \int_0^\infty e^{-\lambda} \lambda^{\frac{\alpha}{2}-1} d\lambda$$

More precisely, for all $f \in C_c^\infty(\mathbb{R}^d)$,

$$\frac{c_\alpha}{|x|^\alpha} \star f = \left(\frac{c_{d-\alpha}}{|k|^{d-\alpha}} \hat{f}(k) \right)^\vee$$

Moreover if $\alpha > \frac{d}{2}$, then we also have

$$\left(\frac{c_\alpha}{|x|^\alpha} \star f \right)^\wedge = \frac{c_{d-\alpha}}{|f|^{d-\alpha}} \hat{f}(k)$$

Lemma 3.22 (Fourier Transform of Gaussians) In \mathbb{R}^d ,

$$\widehat{e^{-\pi|x|^2}} = e^{-\pi|k|^2}$$

More generally for all $\lambda > 0$:

$$\widehat{e^{-\pi\lambda^2|x|^2}} = \lambda^{-d} e^{-\pi\frac{|k|^2}{\lambda^2}}$$

(exercise)

Proof of Theorem. Formally:

$$\begin{aligned} \frac{c_\alpha}{|x|^\alpha} &= \frac{1}{|x|^\alpha} \pi^{-\frac{\alpha}{2}} \int_0^\infty e^{-\lambda} \lambda^{\frac{\alpha}{2}-1} d\lambda = \int_0^\infty e^{-\pi\lambda|x|^2} \lambda^{\frac{\alpha}{2}-1} d\lambda \\ \Rightarrow \frac{\hat{c}_\alpha}{|x|^\alpha}(k) &= \int_0^\infty \widehat{e^{-\pi\lambda|x|^2}}(k) \lambda^{\frac{\alpha}{2}-1} d\lambda = \int_0^\infty \lambda^{-\frac{d}{2}} e^{-\pi\frac{|k|^2}{\lambda}} \lambda^{\frac{\alpha}{2}-1} d\lambda \\ (\lambda \rightarrow \frac{1}{\lambda}) &= \int_0^\infty \lambda^{\frac{d}{2}} e^{-\pi|k|^2\lambda} \lambda^{-\frac{\alpha}{2}+1} \lambda^{-2} d\lambda \\ &= \frac{c_{d-\alpha}}{|k|^{d-\alpha}} \end{aligned}$$

Let $f \in C_c(\mathbb{R}^d)$. Then $\left(\frac{1}{|x|^\alpha} \star f\right)(x) = \int_{\mathbb{R}^d} \frac{1}{|x-y|^\alpha} f(y) dy$ is well defined as $\frac{1}{|x-y|} \in L^1_{loc}(\mathbb{R}^d, dy)$. It is bounded

$$\frac{1}{|x|^\alpha} \star f = \frac{1}{|x|^\alpha} \underbrace{\mathbb{1}(|x| \leq 1)}_{\in L^\infty(\mathbb{R}^d)} \star \underbrace{f}_{L^\infty} + \frac{1}{|x|^\alpha} \underbrace{\mathbb{1}(|x| > 1)}_{\in L^\infty} \star \underbrace{f}_{L^1} \in L^\infty(\mathbb{R}^d)$$

When $|x| \rightarrow \infty$:

$$\left(\frac{1}{|x|^\alpha} \star f\right)(x) = \int_{\mathbb{R}^d} \frac{f(y)}{|x-y|^\alpha} dy = \int_{|y| \leq R} \frac{f(y)}{|x-y|^\alpha} dy \sim \frac{\int_{\mathbb{R}^d} f(y) dy}{|x|^\alpha}$$

Note that $\underbrace{\frac{c_{d-\alpha}}{|k|^{d-\alpha}} \hat{f}(k)}_{\text{bounded}} \in L^1(\mathbb{R}^d)$.

$$\begin{aligned} (\dots) \mathbb{1}(|k| \leq 1) + (\dots) \mathbb{1}(|k| > 1) \frac{1}{|k|^{d-\alpha}} |\hat{f}(k)| \mathbb{1}(|k| \leq 1) &\leq \|f\|_{L^1} \frac{\mathbb{1}(|k| \leq 1)}{|k|^{d-\alpha}} \in L^1(\mathbb{R}^d, dk) \\ \frac{1}{|k|^{d-\alpha}} |\hat{f}(k)| \mathbb{1}(|k| > 1) &\leq |\hat{f}(k)| \in L^2(\mathbb{R}^d, dK) \text{ as } f \in L^2(\mathbb{R}^d) \end{aligned}$$

Lemma 3.23 If $f \in C_c^\infty(\mathbb{R}^d)$, then $\hat{f} \in L^1(\mathbb{R}^d)$

Proof. (Exercise) Hint: $|\widehat{D^\alpha f}| = |2\pi k|^{|\alpha|} |\hat{f}(k)| \rightsquigarrow |\hat{f}(k)| \leq \frac{1}{|k|^{|\alpha|}} \text{ as } |k| \rightarrow \infty.$ ■

Compute:

$$\begin{aligned} \left(\frac{c_{d-\alpha}}{|k|^{d-\alpha}} \hat{f}(k)\right)^\vee(x) &= \int_{\mathbb{R}^d} \frac{c_{d-\alpha}}{|k|^{d-\alpha}} \hat{f}(k) e^{2\pi i k x} dk \\ &= \int_{\mathbb{R}^d} \left(\int_0^\infty e^{-\pi |k|^2 \lambda} \lambda^{\frac{d-\alpha}{2}-1} d\lambda\right) \hat{f}(k) e^{2\pi i k x} dk \\ &= \int_0^\infty \left(\int_{\mathbb{R}^d} e^{-\pi |k|^2 \lambda} \hat{f}(k) e^{2\pi i k x} dk\right) \lambda^{\frac{d-\alpha}{2}-1} d\lambda \\ &= \int_0^\infty \left(e^{-\pi k^2 \lambda} \hat{f}(x)\right)^\vee \lambda^{\frac{d-\alpha}{2}-1} d\lambda \\ &= \int_0^\infty \left(\widehat{\lambda^{-\frac{d}{2}} e^{-\pi \frac{x^2}{\lambda}}(k) \hat{f}(k)}\right)^\vee \lambda^{\frac{d-\alpha}{2}-1} d\lambda \\ &= \int_0^\infty \left(\lambda^{-\frac{d}{2}} e^{-\pi \frac{x^2}{\lambda}} \star f\right) \lambda^{\frac{d-\alpha}{2}-1} d\lambda \\ &= \left(\int_0^\infty \lambda^{-\frac{d}{2}} e^{-\pi \frac{x^2}{\lambda}} \lambda^{\frac{d-\alpha}{2}-1} d\lambda\right) \star f \end{aligned}$$

Assume $d > \alpha > \frac{d}{2}$. Then $\frac{c_\alpha}{|x|^\alpha} \star f \in L^\infty$ and behaves $\frac{c_\alpha(\int f)}{|x|^\alpha}$ as $|x| \rightarrow \infty$. This implies:

$$\int_{\mathbb{R}^d} \left| \frac{c_\alpha}{|x|^\alpha} \star f \right|^2 \leq c + \int_{|x| \geq R} \frac{c}{|x|^{2d}} dx < \infty$$

Thus the Fourier Transform $\widehat{\frac{c_\alpha}{|x|^\alpha} \star f}$ exists. Combining with

$$\begin{aligned} \frac{c_\alpha}{|x|^\alpha} \star f &= \left(\frac{c_{d-\alpha}}{|f|^{d-\alpha}} \hat{f}(k)\right)^\vee \\ \Rightarrow \widehat{\frac{c_\alpha}{|x|^\alpha} \star f} &= \frac{c_{d-\alpha}}{|k|^{d-\alpha}} \hat{f}(k) \end{aligned}$$

■

Remark 3.24 If $d \geq 3$

$$\begin{aligned}\hat{G}(k) &= \frac{1}{|2\pi k|^2} \\ \Rightarrow G(x) &= \left(\frac{1}{|2\pi k|^2} \right)^\vee = \frac{1}{d(d-2)|x|^{d-2}} = \Phi(x)\end{aligned}$$

3.3 Theory of Distribution

Let $\Omega \subseteq \mathbb{R}^d$ be open.

- $D(\Omega) = C_c^\infty(\Omega)$ the space of test functions.
- $\phi_n \rightarrow \phi$ in $D(\Omega)$ if $\exists K \subseteq \Omega$, $\text{supp}(\phi_n), \text{supp}(\phi) \subseteq K$ and $\|D^\alpha(\phi_n - \phi)\|_{L^\infty} \rightarrow 0$ for all $\alpha = (\alpha_1, \dots, \alpha_d)$, $d_i \in \{0, 1, 2, \dots\}$.

$$D'(\Omega) = \{T : D(\Omega) \rightarrow \mathbb{R} \text{ or } \mathbb{C} \text{ linear and continuous}\}$$

the space of distributions.

Motivation: $L^2(\Omega)' = L^2(\Omega)$, $(L^p(\Omega))' = (L^q(\Omega))$, $\frac{1}{p} + \frac{1}{q} = 1$.

Example 3.25 ("normal functions" are distributions) If $f \in L^1_{loc}(\Omega)$, then $T = T_f$ defined by:

$$T(\phi) = \int_{\Omega} f(x)\phi(x) dx$$

is a distribution for all $\phi \in D(\Omega)$, i.e. $T \in D'(\Omega)$. Indeed, it is clear that $T(\phi)$ is well-defined for all $\phi \in D(\Omega)$ and $\phi \mapsto T(\phi)$ is linear. Let us check that $\phi \mapsto T(\phi)$ is continuous. Take $\phi_n \rightarrow \phi$ in $D(\Omega)$ and prove that $T(\phi_n) \rightarrow T(\phi)$. Since $\phi_n \rightarrow \phi$ in $D(\Omega)$, there is a compact K s.t. $\text{supp}(\phi_n), \text{supp}(\phi) \subseteq K \subseteq \Omega$.

Question: Why is $f \mapsto T_f$ injective?

Lemma 3.26 (Fundamental lemma of calculus of variants) Let $\Omega \subseteq \mathbb{R}^d$ be open. If $f, g \in L^1_{loc}(\Omega)$ and $\int_{\Omega} f\phi dy = \int_{\Omega} g\phi dy$ for all $\phi \in D(\Omega)$, then $f = g$ in $L^1_{loc}(\Omega)$

Example 3.27 (Dirac delta function) Let $\Omega \subseteq \mathbb{R}^d$ open. Define $T : D(\Omega) \rightarrow \mathbb{R}$ or \mathbb{C} by $T(\phi) = \phi(x_0)$. Let $x_0 \in \Omega$. Then $T \in D'(\Omega)$ and we denote it by δ_{x_0} . It is clear that $\phi \mapsto T(\phi) = \phi(x_0)$ is well-defined and linear for all $\phi \in D(\Omega)$. Take $\phi_n \rightarrow \phi$ in $D(\Omega)$ and prove $T(\phi_n) \rightarrow T(\phi)$, i.e. $\phi_n(x_0) \rightarrow \phi(x_0)$ (obvious.)

Example 3.28 (Principle Value) The function $f(x) = \frac{1}{x}$ is not in $L^1_{loc}(\mathbb{R})$, but we can still define

$$\int_{\mathbb{R}} f(x)\phi(x) dx = \int_{\mathbb{R}} \frac{\phi(x)}{x} dx$$

for all $\phi \in D(\mathbb{R})$ s.t. $\phi(0) = 0$. In fact,

$$\phi(x) = |\phi(x) - \phi(0)| \leq (\sup |\phi'|)(x),$$

so $\frac{|\phi(x)|}{|x|} \in L^\infty(\mathbb{R})$ and compactly supported. So $\frac{\phi(x)}{x} \in L^1(\mathbb{R})$. Define $T : D(\mathbb{R}) \rightarrow \mathbb{R}$ or \mathbb{C} by

$$T(\phi) = \lim_{\epsilon \rightarrow 0} \int_{|x| \geq \epsilon} \frac{\phi(x)}{x} dx \quad \forall \phi \in D(\mathbb{R}) \text{ s.t. } \phi(0) = 0$$

We denote $T = p.v. \left(\frac{1}{x}\right)$. We check that $T \in D'(\mathbb{R})$: For all $\epsilon > 0$ we have

$$\left| \frac{\phi(x)}{x} \right| \leq \frac{\|\phi\|_{L^\infty}}{\epsilon}$$

for all $|x| \geq \epsilon$ and ϕ is compactly supported. So we get for all $\epsilon > 0$:

$$\mathbb{1}(|x| \geq \epsilon) \frac{\phi(x)}{x} \in L^1(\mathbb{R}) \rightsquigarrow \int_{|x| \geq \epsilon} \frac{\phi(x)}{x} dx < \infty$$

We can write:

$$\int_{|x| \geq \epsilon} \frac{\phi(x)}{x} dx = \int_{|x| \geq 1} \frac{\phi(x)}{x} dx + \int_{\epsilon \leq |x| \leq 1} \frac{\phi(x)}{x} dx$$

The second part can be written as:

$$\int_{\epsilon \leq |x| \leq 1} \frac{\phi(x)}{x} dx = \int_{\epsilon}^1 \frac{\phi(x)}{x} dx + \int_{-1}^{-\epsilon} \frac{\phi(x)}{x} dx = \int_{\epsilon}^1 \frac{\phi(x) - \phi(-x)}{x} dx$$

Since $\phi \in C_c^\infty(\mathbb{R})$ it holds that $|\phi(x) - \phi(-x)| \leq 2\|\phi'\|_{L^\infty}(x)$.

$$\begin{aligned} \Rightarrow \frac{\phi(x) - \phi(-x)}{x} &\in L^\infty(\mathbb{R}) \Rightarrow \frac{\phi(x) - \phi(-x)}{x} \in L^1(0, 1) \\ \Rightarrow \int_0^1 \frac{\phi(x) - \phi(-x)}{x} dx &= \lim_{\epsilon \rightarrow 0} \int_{\epsilon}^1 \frac{\phi(x) - \phi(-x)}{x} dx \end{aligned}$$

Remark 3.29 The function $\frac{1}{|x|^d}$ is not in $L_{loc}^1(\mathbb{R}^d)$ but $\exists T \in D'(\mathbb{R}^d)$ s.t. $T(\phi) = \int_{\mathbb{R}^d} \frac{\phi(x)}{|x|^d} dx$ for all $\phi \in C_c^\infty(\mathbb{R}^d)$ s.t. $\phi(0) = 0$

Let in the following $\mathbb{K} \in \{\mathbb{R}, \mathbb{C}\}$.

Definition 3.30 (Derivatives of distributions) Let $\Omega \subseteq \mathbb{R}^d$ and $T \in D'(\Omega)$. Define for $\alpha \in \mathbb{N}^d$:

$$\begin{aligned} D^\alpha T : D(\Omega) &\longrightarrow \mathbb{K} \\ \phi &\longmapsto (-1)^{|\alpha|} T(D^\alpha \phi) \end{aligned}$$

Motivation: $f \in C_c^\infty(\Omega)$

$$\int_{\Omega} (D^\alpha f) \phi = (-1)^{|\alpha|} \int_{\Omega} f (D^\alpha \phi)$$

„If the classical derivative exists, then it is the same as the distributional derivative.“
We write

$$(D^\alpha T)(\phi) = T_{D^\alpha f}(\phi) = (-1)^{|\alpha|} T_f(D^\alpha \phi).$$

Remark 3.31 For all $T \in D'(\Omega)$ it holds $D^\alpha T \in D'(\Omega)$ for all $\alpha \in \mathbb{N}^d$. Clearly

$$\phi \mapsto (D^\alpha T)(\phi) = (-1)^{|\alpha|} T(D^\alpha \phi)$$

is linear. Moreover, if $\phi_n \rightarrow \phi$ in $D(\Omega)$, then $D^\alpha \phi_n \rightarrow D^\alpha \phi$ in $D(\Omega)$, so

$$(D^\alpha T)(\phi_n) = (-1)^{|\alpha|} T(D^\alpha \phi_n) \xrightarrow{n \rightarrow \infty} (-1)^{|\alpha|} T(D^\alpha \phi) = (D^\alpha T)(\phi)$$

Example 3.32 Consider $f : x \mapsto |x|$, then $f \in C(\mathbb{R})$ but $f \notin C^1(\mathbb{R})$. However,

$$f'(x) = g(x) = \begin{cases} 1 & x \geq 0 \\ -1 & x < 0 \end{cases} \in L^1_{loc}$$

Lets check $f' = g$, i.e. $-f(\phi') = f'(\phi) = g(\phi)$ for all $\phi \in D(\mathbb{R})$. Thus we need to prove:

$$-\int_{\mathbb{R}} f(x) \phi'(x) dx = \int_{\mathbb{R}} g(x) \phi(x) dx \quad \forall \phi \in D(\mathbb{R})$$

namely:

$$\underbrace{-\int_{\mathbb{R}} |x| \phi'(x) dx}_{:= (\star)} = \int_0^\infty \phi(x) dx - \int_{-\infty}^0 \phi(x) dx$$

Now we have

$$(\star) = -\int_0^\infty x \phi'(x) dx + \int_{-\infty}^0 x \phi'(x) dx.$$

By integration by parts:

$$\int_0^\infty x \phi'(x) dx = \underbrace{[x \phi(x)]_0^\infty}_{=0} - \int_0^\infty \phi(x) dx = -\int_0^\infty \phi(x) dx$$

and similiary:

$$\int_{-\infty}^0 x \phi'(x) dx = -\int_{-\infty}^0 \phi(x) dx$$

Thus $f' = g$ in $D'(\Omega)$. We claim that $g' = 2\delta_0$ in $D'(\mathbb{R})$. In fact, for all $\phi \in D(\mathbb{R})$, then:

$$\begin{aligned} g'(\phi) &= -g(\phi') = -\int_{\mathbb{R}} g \phi' dx = -\int_{-\infty}^0 (-1) \phi' dx - \int_0^\infty (1) \phi' dx \\ &= -\int_0^\infty \phi' dx + \int_{-\infty}^0 \phi' dx = [\phi(0) - \underbrace{\phi(\infty)}_{=0}] + [\phi(0) - \underbrace{\phi(-\infty)}_{=0}] = 2\phi(0) = 2\delta_0(\phi) \end{aligned}$$

So $g' = 2\delta_0$ in $D'(\mathbb{R})$.

Exercise 3.33 Prove that $(D^\alpha \delta_x)(\phi) = (-1)^{|\alpha|} (D^\alpha \phi)(x)$ for all $\phi \in D(\mathbb{R})$ for all $x \in \mathbb{R}$.

Definition 3.34 (Convergence of distributions) Let $\Omega \subseteq \mathbb{R}^d$ be open, then

$$T_n \xrightarrow{n \rightarrow \infty} T$$

in $D'(\Omega)$ if $T_n(\phi) \xrightarrow{n \rightarrow \infty} T(\phi)$ for all $\phi \in D(\Omega)$.

Exercise 3.35 Let $f \in L^1(\mathbb{R}^d)$, $\int f = 1$ For $\epsilon > 0$, define $f_\epsilon(x) = \epsilon^{-d} f(\epsilon^{-1}x)$. Then: $f_\epsilon \rightarrow \delta_0$ in $D'(\Omega)$.

Exercise 3.36 Let $\Omega \subseteq \mathbb{R}^d$ be open and $T_n \rightarrow T$ in $D'(\Omega)$. Then: $D^\alpha T_n \rightarrow D^\alpha T$ in $D'(\Omega)$ for all $\alpha = (\alpha_1, \dots, \alpha_d)$

Definition 3.37 (Convolution of distributions) Let $T \in D'(\mathbb{R})$ and $f \in L_c^\infty(\mathbb{R}^d)$. Define

$$(T \star f)(y) = T(f_y)$$

We write $f_y(x) = f(x - y)$ and $\tilde{f}(x) = f(-x)$.

Theorem 3.38 Let $T \in D'(\mathbb{R})$. Then for all $f \in D(\mathbb{R})$:

1. $y \mapsto T(f_y)$ is $C^\infty(\mathbb{R}^d)$ and

$$D_y^\alpha (T(f_y)) = (D^\alpha T)(f_y) = (-1)^{|\alpha|} T(D^\alpha f_y)$$

2. For all $g \in L^1(\mathbb{R}^d)$ and compactly supported, then

$$\int_{\mathbb{R}^d} g(y) T(f_y) dy = T(\underbrace{f \star g}_{\in C_c^\infty(\mathbb{R})})$$

Proof. 1. We prove that $y \mapsto T(f_y)$ is continuous. Take $y_n \rightarrow y$ in \mathbb{R}^d , then:

$$T(f_{y_n}) \rightarrow T(f_y)$$

since $f_{y_n} \rightarrow f_y$ in $D(\mathbb{R}^d)$. We check this: Since $f \in C_c^\infty(\mathbb{R}^d)$, it holds that $\text{supp } f \subseteq B(0, R) \subseteq \mathbb{R}^d$. Since $y_n \rightarrow y$ in \mathbb{R}^d . We have $\sup_n |y_n| < \infty$. Thus f_{y_n}, f_y are supported in $\overline{B(0, R + \sup_n |y_n|)} = K$ compact. Moreover

$$|f_{y_n}(x) - f_y(x)| = |f(x - y_n) - f(x - y)| \leq \|\nabla f\|_{L^\infty} \|y_n - y\| \rightarrow 0$$

So we get $\|f_{y_n} - f_y\|_{L^\infty} \rightarrow 0$ Similary:

$$\|D^\alpha f_{y_n} - D^\alpha f_y\|_{L^\infty} \rightarrow 0$$

■

Exercise 3.39 (E 3.1 Lebesgue Differentiation Theorem) Let $f \in L_{loc}^1(\mathbb{R}^d)$. Prove that that for almost every $x \in \mathbb{R}^d$:

$$\oint_{B(x,r)} |f(x) - f(y)| dy \xrightarrow{r \rightarrow 0} 0$$

Proof. Clearly the same result holds with $\mathbb{R}^d \rightsquigarrow \Omega \subseteq \mathbb{R}^d$ open. Also it suffices to consider $f \in L^1(\mathbb{R}^d)$. From the last time discussion, by a density argument there exists $r_n \rightarrow 0$ s.t.

$$\oint_{B(x,r_n)} |f(y) - f(x)| dy = 0$$

for a.e. $x \in \mathbb{R}^d$. We prove that for all $\epsilon > 0$, te set $A_\epsilon = \{x \in \mathbb{R}^d \mid \limsup_{r \rightarrow 0} \oint_{B(x,r)} |f(y) - f(x)| dy > \epsilon\}$ has measure 0. This will imply that

$$\bigcup_{n=1}^{\infty} A_{\frac{1}{n}} = \left\{ x \in \mathbb{R}^d \mid \limsup_{r \rightarrow 0} \int_{B(x,r)} |f(y) - f(x)| dy > 0 \right\}$$

has measure 0, which is what we want to show. First, we show that $|A_\epsilon| = 0$: Take $\{f_n\} \subseteq C_c^\infty$, $f_n \rightarrow f$ in $L^1(\mathbb{R}^d)$. By the triangle inequality:

$$|f(y) - f(x)| \leq |f(y) - f_n(y)| + |f_n(y) - f_n(x)| + |f_n(x) - f(x)|$$

So we get

$$\begin{aligned} & \int_{B(x,r)} |f(y) - f(x)| dy \\ & \leq \int_{B(x,r)} |f(y) - f_n(y)| dy + \int_{B(x,r)} |f_n(y) - f_n(x)| + |f_n(x) - f(x)| \\ \Rightarrow \quad \limsup_{r \rightarrow 0} \dots & \leq \limsup_{r \rightarrow 0} (\dots) + 0 + |f_n(x) - f(x)| \end{aligned}$$

Thus, for all $x \in A_\epsilon$, then:

$$\limsup_{r \rightarrow 0} \int_{B(x,r)} |f_n(y) - f(y)| dy + |f_n(x) - f(x)| > 2\epsilon$$

Observation: If $a, b \geq 0$, $a + b > 2\epsilon$ then either $a > \epsilon$ or $b > \epsilon$. Therefore $A_\epsilon \subseteq (S_{n,\epsilon} \cup \tilde{S}_{n,\epsilon})$, where

$$\begin{aligned} S_{n,\epsilon} &= \{x \mid |f_n(x) - f(x)| > \epsilon\} \\ \tilde{S}_{n,\epsilon} &= \{x \mid \limsup_{r \rightarrow 0} \int_{B(x,r)} |f_n(y) - f(y)| dy > \epsilon\} \end{aligned}$$

Consequently: $|A_\epsilon| \leq |S_{n,\epsilon}| + |\tilde{S}_{n,\epsilon}|$ for all $n \geq 1$. By the Markov / Chebyshev inequality:

$$|S_{n,\epsilon}| \leq \int_{S_{n,\epsilon}} \frac{|f_n(x) - f(x)|}{\epsilon} dx = \int_{\mathbb{R}^d} \frac{|f_n(x) - f(x)|}{\epsilon} dx = \frac{\|f_n - f\|_{L^1}}{\epsilon}$$

We want to prove a simpler bound for $\tilde{S}_{n,\epsilon}$. For all $x \in \tilde{S}_{n,\epsilon}$:

$$\limsup_{r \rightarrow 0} \int_{B(x,r)} |f_n(x) - f(y)| dy > \epsilon$$

So there is a $r_x \in (0, 1)$ s.t.

$$\int_{B(x, r_x) = B_x} |f_n(y) - f(y)| dy > \epsilon$$

Thus $\tilde{S}_{n,\epsilon} \subseteq \left(\bigcup_{x \in \tilde{S}_{n,\epsilon}} B_x \right)$.

Lemma 3.40 (Vitali Covering) If F is a collection of balls in \mathbb{R}^d with bounded radius, then there exists a sub-collection $G \subseteq F$ s.t.

- G has disjoint balls
- $\bigcup_{B \in F} B \subseteq \bigcup_{B \in G} 5B, 5B(x, r) = B(x, 5r)$

Remark 3.41 The condition of the boundedness of the radius is necessary. Otherwise, consider $\{B(0, n)\}_{n=1}^\infty$

Here consider $F = \{B_x\}_{x \in \tilde{S}_{n,\epsilon}}$. With the Vitali covering lemma there is a $G \subseteq F$ s.t. G contains disjoint balls and:

$$\tilde{S}_{n,\epsilon} \subseteq \bigcup_{B \in F} B \subseteq \bigcup_{B \in G} 5B$$

So we get

$$|\tilde{S}_{n,\epsilon}| \leq \left| \bigcup_{B \in G} 5B \right| \leq \sum_{B \in G} |5B| = \sum_{B \in G} 5^d |B|$$

On the other hand, for all $B \in G \subseteq F$:

$$\int_B |f_n(y) - f(y)| dy > \epsilon \Rightarrow \int_B |f_n - f| > \epsilon |B|$$

This implies:

$$\sup_{B \in G} \int_B |f_n - f| > \epsilon \sum_{B \in G} |B|$$

Since balls in G are disjoint:

$$\int_{\mathbb{R}^d} \geq \int_{\bigcup_{B \in G}} |f_n - f| dy > \epsilon \sum_{B \in G} |B| \geq \frac{\epsilon}{5^d} |\tilde{S}_{n,\epsilon}|$$

So

$$|\tilde{S}_{n,\epsilon}| \leq \frac{5^d}{\epsilon} \|f_n - f\|_{L^1}$$

In summary:

$$|A_\epsilon| \leq |S_{n,\epsilon}| + |\tilde{S}_{n,\epsilon}| \leq \frac{5^d + 1}{\epsilon} \|f_n - f\|_{L^1} \rightarrow 0$$

as $n \rightarrow \infty$. So $|A_\epsilon| = 0$ for all $\epsilon > 0$ ■

Remark 3.42 1. The proof can be done by using the Besicovitch covering lemma: For all $E \subseteq \mathbb{R}^d$ s.t. E is bounded. Let $F =$ collection of balls s.t. for all $x \in E$ there is a $B_x \in F$ s.t. x is the center of B_x . There is a sub-collection $G \subseteq F$ s.t.

- $E \subseteq \bigcup_{B \in G} B$
- Any point in E belongs to at most C_d balls in G (C_d depends only on \mathbb{R}^d), i.e.

$$\mathbb{1}_E(x) \leq \sum_{B \in G} \mathbb{1}_B(x) \leq C_d \mathbb{1}_E(x) \forall x$$

2. By a simpler argument we can prove the weak L^1 -estimate:

$$\{x \mid f^\star(x) > \epsilon\} \leq \frac{C_d}{\epsilon} \|f\|_{L^1(\mathbb{R}^d)}$$

(Hardy-Littlewood maximal function)

Exercise 3.43 (E 3.2) Let $1 \leq p, q, r \leq 2$, $\frac{1}{p} + \frac{1}{q} = 1 + \frac{1}{r}$. Recall that if $f \in L^p(\mathbb{R}^d)$, $g \in L^q(\mathbb{R}^d)$, then $f \star g \in L^r(\mathbb{R}^d)$ by Young's Inequality, and its Fourier transform is well-defined by the Hausdorff-Young inequality. Prove that

$$\widehat{f \star g}(k) = \hat{f}(k) \hat{g}(k) \quad \forall k \in \mathbb{R}^d$$

Hint: In the lecture we already discussed the case $f, g \in C_c(\mathbb{R}^d)$.

Solution.

Step 1) $f, g \in C_c^\infty(\mathbb{R}^d)$ (Fubini)

Step 2) $f \in L^p, g \in L^q$, find $f_n, g_n \in C_c^\infty$ s.t. $f_n \rightarrow f$ in L^p , $g_n \rightarrow g$ in L^q . $\widehat{f_n \star g_n} = \widehat{f_n} \widehat{g_n}$ pointwise a.e. we have

$$\begin{aligned}
 (\text{Hausdorff-Young}) \quad & \|\widehat{f \star g} - \widehat{f_n \star g_n}\|_{L^{r'}} \\
 & \leq \|\widehat{f \star g} - \widehat{f_n \star g_n}\|_{L^r} \\
 & = \|(f - f_n) \star g_n + f_n \star (g_n - g)\|_{L^r} \\
 & \leq \|(f - f_n) \star g_n\|_{L^r} + \|f_n \star (g_n - g)\|_{L^r} \\
 (\text{Young}) \quad & \leq \|f - f_n\|_{L^p} \|g_n\| + \|f_n\|_{L^p} \|g_n - g\|_{L^q} \xrightarrow{n \rightarrow \infty} 0
 \end{aligned}$$

Moreover:

$$\begin{aligned}
 \|\widehat{f_n g_n} - \widehat{f g}\|_{L^{r'}} & = \|(\widehat{f_n} \widehat{g_n}) - \widehat{f g}\|_{L^{r'}} \\
 (\text{Hölder}) \quad & \leq \|\widehat{f_n} - \widehat{f}\|_{L^{p'}} \|\widehat{g_n}\|_{L^{q'}} + \|\widehat{f}\|_{L^{q'}} \\
 (\text{Hausdorff-Young (3.19)}) \quad & \leq \|f_n - f\|_{L^p} \|g_n\|_{L^q} + \|f\|_{L^p} \|g_n - g\|_{L^q} \xrightarrow{n \rightarrow \infty} 0 \\
 \text{So } \widehat{f_n g_n} & \rightarrow \widehat{f g} \text{ in } L^{r'} \quad \widehat{f \star g} = \widehat{f g} \text{ in } L^{r'} \quad \frac{1}{r'} = \frac{1}{p'} + \frac{1}{q'} \quad \blacksquare
 \end{aligned}$$

Exercise 3.44 (E 3.3) $f \in C_c^\infty(\mathbb{R}^d)$. Prove $|\hat{f}(k)| \leq \frac{C_N}{(1+|k|)^N}$

Solution. Since $f \in C_c^\infty$ we have that $D^\alpha f \in C_c^\infty$. Recall

$$\widehat{D^\alpha f}(k) = (-2\pi i k)^\alpha \hat{f}(k)$$

For example

$$\begin{aligned}
 \widehat{-\Delta f}(k) & = |2\pi i k|^2 \hat{f}(k) \\
 (\text{Induction}) \rightsquigarrow \widehat{(-\Delta)^N f}(k) & = |2\pi k|^{2N} \hat{f}(k)
 \end{aligned}$$

So we can conclude

$$\hat{f}(k) = \frac{\widehat{(-\Delta)^N f}(k)}{|2\pi k|^{2N}} \quad \forall k \in \mathbb{R}^d$$

1. $f \in C_c^\infty \subseteq L^1(\mathbb{R}^d) \Rightarrow \hat{f} \in L^\infty$
2. $(-\Delta)^N f \in C_c^\infty \subseteq L^1(\mathbb{R}^d) \Rightarrow \widehat{(-\Delta)^N f} \in L^\infty$

$$\text{Conclusion: } \hat{f}(k) \leq \begin{cases} C & \forall k \\ \frac{C_N}{|k|^{2N}} & \forall k \end{cases} \text{ So } \hat{f}(k) \leq \frac{C_N}{(1+|k|)^N} \quad \blacksquare$$

Exercise 3.45 (E 3.4)

Proof. Siehe Goodnotes \blacksquare

Exercise 3.46 (Bonus 3) Let $f \in L^1(\mathbb{R}^d)$ such that

$$|\hat{f}(k)| \leq \frac{C_N}{(1+|k|)^N}$$

for all $k \in \mathbb{R}^d$, for all $N \geq 1$. (C_N is independent of k). Prove that $f \in C^\infty(\mathbb{R}^d)$

$(f \in C^\infty)$ i.e. $\exists \tilde{f} \in C^\infty$ s.t. $f = \tilde{f}$ a.e.

Theorem 3.47 Take $T \in D'(\mathbb{R})$, $f \in C_c^\infty(\mathbb{R}^d) = D(\mathbb{R}^d)$, $f_y(x) = f(x - y)$

- a) $y \mapsto T(f_y) \in C^\infty(\mathbb{R}^d)$ and $D_y^\alpha(T(f_y)) = (D^\alpha T)(f_y) = (-1)^{|\alpha|} T(D_x^\alpha f_y)$
b) $\forall g \in L^1(\mathbb{R}^d)$ and compactly supported

$$\int_{\mathbb{R}^d} g(y) T(f_y) dy = T\left(\underbrace{f \star g}_{\in C_c^\infty}\right)$$

Proof. a) $y \mapsto T(f_y)$ is continuous since $y_n \rightarrow y$ in \mathbb{R}^d , then $f_{y_n} \rightarrow f_y$ implies $T(f_{y_n}) \rightarrow T(f_y)$. Let's check that $y \mapsto T(f_y) \in C^1$:

$$\lim_{h \rightarrow 0} \frac{T(f_{y-he_i}) - T(f_y)}{h} = \lim_{h \rightarrow 0} T\left(\frac{f_{y-he_i} - f_y}{h}\right)$$

We have $\frac{f_{y-he_i} - f_y}{h} \xrightarrow{h \rightarrow 0} (\partial_i f)_y$ in $D(\mathbb{R}^d)$

- $\exists K$ compact set such that $\text{supp}(f_{y-he_i} - f_y), \text{supp } \partial_i f \subseteq K$ as $|h|$ small.

$$\begin{aligned} & \bullet \frac{f_{y-he_i}(x) - f_y(x)}{h} - (\partial_i f)_y(x) \\ &= \frac{f(x - y + he_i) - f(x - y)}{h} - (\partial_i f)(x - y) \end{aligned}$$

$$\left| \int_0^1 \partial_i f(x - y + the_i) dt - \partial_i f(x - y) \right| \xrightarrow{h \rightarrow 0} 0 \text{ uniformly in } x$$

Similary:

$$\begin{aligned} & \left| D_x^\alpha \left(\frac{f(x - y + he_i) - f(x - y)}{h} - (\partial_i f)(x - y) \right) \right| \\ &= \left| \frac{D_x^\alpha f(x - y + he_i) - D_x^\alpha f(x - y)}{h} - \partial_i(D_x^\alpha f)(x - y) \right| \xrightarrow{h \rightarrow 0} 0 \end{aligned}$$

uniformly in x . Conclude:

$$\lim_{h \rightarrow 0} \frac{T(f_{y-he_i}) - T(f_y)}{h} \xrightarrow{h \rightarrow 0} T((\partial_i f)_y) \in C(\mathbb{R}^d)$$

So we get that $y \mapsto T(f_y) \in C^1$ and $-\partial_{y_i} T(f_y) = T((\partial_i f)_y)$

By induction:

$$D_y^\alpha T(f_y) = (-1)^{|\alpha|} T((D^\alpha f)_y) = (D^\alpha T)(f_y) \quad \forall \alpha \in \mathbb{N}^d$$

- b) Heuristic: $T = T(x)$

$$\begin{aligned} \int_{\mathbb{R}^d} g(y) T(f_y) dy &= \int_{\mathbb{R}^d} g(y) \left(\int_{\mathbb{R}^d} T(x) f(x - y) dx \right) dy \\ &= \int_{\mathbb{R}^d} T(x) \left(\int_{\mathbb{R}^d} g(y) f(x - y) dy \right) dx \\ &= \int_{\mathbb{R}^d} T(x) (f \star g)(x) dx = T(f \star g) \end{aligned}$$

Step 1: $g \in C_c^\infty(\mathbb{R}^d)$

$$\begin{aligned}
(\text{Riemann Sum}) \quad \int_{\mathbb{R}^d} g(y)T(f_y) dy &= \lim_{\Delta_N \rightarrow 0} \Delta_N \sum_{j=1}^N g(y_j)T(f_{y_j}) \\
&= \lim_{\Delta_N \rightarrow 0} T\left(\Delta_N \sum_{j=1}^N g(y_j)f_{y_j}\right) \\
&= T(f \star g)
\end{aligned}$$

because

$$\begin{aligned}
&\lim_{\Delta_N \rightarrow 0} \Delta_N \sum_{j=1}^N g(y_j)f_{y_j}(x) \rightarrow (f \star g)(x) \text{ in } D(\mathbb{R}^d) \\
&\lim_{\Delta_N \rightarrow 0} \Delta_N \sum_{j=1}^N g(y_j)f(x - y_j) \xrightarrow{\text{Riemann}} \int_{\mathbb{R}^d} g(y)f(x - y) dy = (f \star g)(x)
\end{aligned}$$

Proof of:

$$\lim_{\Delta_N \rightarrow 0} \Delta_N \sum_{j=1}^N g(y_j)f(x - y_j) \rightarrow (f \star g)(x) \text{ in } D(\mathbb{R}^d)$$

1) Since $f, g \in C_c^\infty$ we have $f \star g \in C_c^\infty$. And we have

$$x \mapsto \Delta_N \sum_{j=1}^N g(y_j)f(x - y_j) \in C^\infty$$

since $f \in C^\infty$ supported in $(\text{supp } g + \text{supp } f)$. So all functions are C_c^∞ and supported in $(\text{supp } g + \text{supp } f)$.

2)

$$\left| \lim_{\Delta_N \rightarrow 0} \Delta_N \sum_{j=1}^N g(y_j)f(x - y_j) - \int_{\mathbb{R}^d} g(y)f(x - y) dy \right| \xrightarrow{\Delta_N \rightarrow 0} 0$$

uniformly in x . (Result from the Riemann-Sum)

3)

$$\begin{aligned}
&\left| D_x^\alpha \left(\Delta_N \sum_{j=1}^N g(y_j)f(x - y_j) - (f \star g)(x) \right) \right| \\
&= \left| \Delta_N \sum_{j=1}^N g(y_j)D^\alpha f(x - y_j) - (D^\alpha f) \star g(x) \right| \xrightarrow{\Delta_N \rightarrow 0} 0
\end{aligned}$$

uniformly in x for all α .

Step 2: Take $g \in L^1(\mathbb{R}^d)$ and compactly supported. Then $\exists \{g_n\} \subseteq C_c^\infty(\mathbb{R}^d)$, $\text{supp } g_n \subseteq \text{supp } g + B(0, 1)$ such that $g_n \rightarrow g$ in $L^1(\mathbb{R}^d)$. By Step 1:

$$\int_{\mathbb{R}^d} g_n(y)T(f_y) dy = T(g_n \star f)$$

Take $n \rightarrow \infty$:

$$\int_{\mathbb{R}^d} g_n(y)T(f_y) dy \rightarrow \int_{\mathbb{R}^d} g(y)T(f_y) dy$$

since $g_n \rightarrow g$ in L^1 compactly supported and $y \mapsto T(f_y) \in C^\infty \subseteq L^\infty(K)$.
Moreover (exercise):

$$\underbrace{g_n \star f}_{\in C_c^\infty} \rightarrow g \star f \quad \text{in } D(\mathbb{R}^d)$$

So $T(g_n \star f) \xrightarrow{n \rightarrow \infty} T(g \star f)$. Finally we obtain:

$$\int g(y)T(f_n) dy = T(g \star f) \quad \blacksquare$$

Theorem 3.48 Let $\Omega \subseteq \mathbb{R}^d$ be open. Let $T \in D'(\Omega)$ and $f \in C_c^\infty(\Omega)$. Denote

$$\Omega_f = \{y \in \mathbb{R}^d \mid \text{supp } f_y = y + \text{supp } f \subseteq \Omega\}$$

a) $y \mapsto T(f_y) \in C^\infty(\Omega_f)$ and $D_y^\alpha(T(f_y)) = (D^\alpha T)(f_y) = (-1)^{|\alpha|} T((D^\alpha f)_y)$

b) For all $g \in L^1(\Omega_g)$ compactly supported in Ω_f and it holds:

$$\int_{\Omega} g(y)T(f_y) dy = T(f \star g).$$

Theorem 3.49 Let $T \in D'(\Omega)$ s.t. $\nabla T = 0$ in $D'(\Omega)$. Then: $T = \text{const.}$ in Ω .

Proof. ($\Omega = \mathbb{R}^d$) for all $f \in C_c^\infty$, $y \mapsto T(f_y) \in C^\infty(\mathbb{R}^d)$ and $\partial_{y_i} T(f_y) = (\partial_j T)(f_y) = 0$ for all $i = 1, \dots, d$. Then by the result of the theorem for C^∞ functions, $y \mapsto T(f_y) = \text{const}$ independent of y . Consequently:

$$T(f_y) = T(f_0) = T(f) \quad \forall y \in \mathbb{R}^d \quad \forall f \in C_c^\infty(\mathbb{R}^d)$$

For any $g \in C^\infty(\mathbb{R}^d)$:

$$\left(\int_{\mathbb{R}^d} g dy \right) T(f) = \int_{\mathbb{R}^d} g(y)T(f_y) dy = T(f \star g) = T(g \star f) = \left(\int_{\mathbb{R}^d} f dy \right) T(g)$$

So $\frac{T(f)}{\int_{\mathbb{R}^d} f}$ is independent of f (as soon as $\int f \neq 0$). So we get that $T(f) = \text{const} \int_{\mathbb{R}^d} f$, where const is independent of f . \blacksquare

Remark 3.50 If $u \in C^1(\mathbb{R}^d)$, then:

$$u(x+y) - u(x) = \int_0^1 \sum_{j=1}^d y_j (\partial_j u)(x + ty_j) dt = \int_0^1 y \nabla u(x + ty) dt$$

So we get that if $\nabla u = 0$, then $u(x+y) - u(x) = 0$ for all x, y , so $u = \text{const.}$

Theorem 3.51 (Taylor expansion for distributions) Let $T \in D'(\mathbb{R}^d)$ and $f \in C_c^\infty(\mathbb{R}^d)$. Then $y \mapsto T(f_y) \in C^\infty$ and

$$T(f_y) - T(f) = \int_0^1 \sum_{j=1}^d y_j (\partial_j T)(f_{ty}) dt.$$

In particular, if $g \in L_{loc}^1$ and $\nabla g \in L_{loc}^1$, then $\forall y \in \mathbb{R}^d$:

$$g(x+y) - g(x) = \int_0^1 g(x+ty)y dt$$

for a.e. $x \in \mathbb{R}^d$.

Proof. $y \mapsto T(f_y)$ is C^∞ and $\frac{d}{dt}[T(f_{ty})] = (\nabla T)(f_{ty})y$ So we get

$$\begin{aligned} T(f_y) - T(f) &= \int_0^1 \frac{d}{dt}(T(f_{ty})) dt \\ &= \int_0^1 (\nabla T)(f_{ty})y dt \\ &= \int_0^1 \sum_{j=1}^d (\partial_j T)(f_{ty})y_j dt \end{aligned} \quad \blacksquare$$

Corrolary 3.52 Let $g \in L^1_{loc}(\mathbb{R}^d)$ s.t. $\partial_j g \in L^1_{loc}(\mathbb{R}^d)$ for all $j = 1, 2, \dots, d$ (i.e. $g \in W^{1,1}_{loc}(\mathbb{R}^d)$). Then for all $y \in \mathbb{R}^d$:

$$\begin{aligned} g(x+y) - g(x) &= \int_0^1 y \cdot \nabla g(x+ty) dt \\ &= \int_0^1 \sum_{j=1}^d y_j \partial_j g(x+ty) dt \end{aligned}$$

for a.e. x .

Proof. For all $f \in C^\infty_c$ we have

$$\begin{aligned} \int_{\mathbb{R}^d} f(x)[g(x+y) - g(x)] dx &= \int_{\mathbb{R}^d} g(x)[f(x-y) - f(x)] dx \\ &= g(f_y) - g(f) \\ &= \int_0^1 \sum_{j=1}^d y_j (\partial_j g)(f_{ty}) dt \\ &= \int_0^1 \sum_{j=1}^d y_j \int_{\mathbb{R}^d} \sum_{j=1}^d y_j \left[\int_{\mathbb{R}^d} (\partial_j g)(x) f_{ty}(x) dx \right] \\ &= \int_0^1 \sum_{j=1}^d y_j \left[\int_{\mathbb{R}^d} (\partial_j g)(x+ty) f(x) dx \right] dt \\ &= \int_{\mathbb{R}^d} f(x) \left[\int_0^1 \sum_{j=1}^d y_j \partial_j g(x+ty) dt \right] dx \end{aligned}$$

For all $\phi \in C^\infty_c$: $= g(x+y) - g(x)$ a.e. $x \in \mathbb{R}^d$. \blacksquare

Remark 3.53 If $T \in D'(\Omega)$, $\Omega \subseteq \mathbb{R}^d$ open, if $y \nabla T = 0$, then $T = \text{const}$.

Theorem 3.54 (Equivalence of the classical and distributional derivatives) Let $\Omega \subseteq \mathbb{R}^d$. Then the following are equivalent:

1. $T \in D'(\Omega)$ s.t. $\partial_{x_i} T = g_i \in C(\Omega)$ for all $i = 1, \dots, d$.
2. $T = f \in C^1(\Omega)$ and $g_i = \partial_{x_i} f$

Proof.

(2) \Rightarrow (1): If $T = f \in C^1(\Omega)$, then: $\partial_{x_i} f \in C(\Omega)$.

$$\partial_{x_i} T(\phi) = -T(\partial_{x_i} \phi) = - \int_{\Omega} f(\partial_{x_i} \phi) = \int_{\Omega} (\partial_{x_i} f) \phi$$

for all $\phi \in D(\Omega)$, so $\partial_{x_i} T = \partial_{x_i} f$.

(1) \Rightarrow (2): Why is $T = f \in C^1(\Omega)$? As $\partial_{x_i} f = g_i$:

$$f(x+y) - f(x) = \int_0^1 \nabla f(x+ty) y dt = \int_0^1 \sum_{i=1}^d g_i(x+ty) y_i dt$$

So we get

$$f(y) = f(0) + \int_0^1 \sum_{i=1}^d g_i(ty) g_i dt.$$

We expect that $f \in C^1$ and $\partial_{x_i} f = g_i$. But this is not trivial to prove.

$$\begin{aligned} \frac{f(y+he_i) - f(y)}{h} &= \int_0^1 \sum_{i=1}^d [g_i(ty+the_i)(y_i+h\delta_{ij})] dt \\ &= \int_0^1 g_i(ty+the_i) dt + \int_0^1 \sum_{j \neq i} \frac{[g_i(ty+the_i) - g_i(ty)]}{h} y_j dt \\ &\xrightarrow{h \rightarrow 0} \int_0^1 g_i(ty) dt + \text{is difficult ...} \end{aligned}$$

Lets take $\phi \in C_c^\infty$, then:

$$\begin{aligned} T(\phi_y) - T(\phi) &= \int_0^1 \underbrace{\nabla T}_{(g_i)_{i=1}^d}(\phi_{ty}) y dt \\ &= \int_0^1 \sum_{i=1}^d \left(\int_{\Omega} g_i(x) \underbrace{\phi_{ty}}_{=\phi(x-ty)} dx \right) dt \\ &= \int_{\mathbb{R}^d} \left(\sum_{i=1}^d \int_0^1 g_i(x) \phi(x-ty) y_i dt \right) dx \\ &= \int_{\mathbb{R}^d} \left(\sum_{i=1}^d \int_0^1 g_i(x+ty) \phi(x) y_i dt \right) dx \\ &= \int_{\mathbb{R}^d} \left(\sum_i \int_0^1 g_i(x+ty) y_i dt \right) \phi(x) dx \end{aligned}$$

Integrating against $\psi(y)$ with $\psi \in C_c^\infty$:

$$\begin{aligned} &\int_{\mathbb{R}^d} T(\phi_y) \psi(y) dy - T(\phi) \int_{\mathbb{R}^d} \psi(y) dy \\ &= \int_{\mathbb{R}^d} \left(\int_{\mathbb{R}^d} \sum_i \int_0^1 g_i(x+ty) y_i \psi(y) dt dy \right) \psi(x) dx \\ &\Rightarrow T(\phi \star \psi) - T(\phi) \int \psi = \dots \\ &\Rightarrow \int_{\mathbb{R}^d} T(\psi_y) \phi(y) dy - T(\phi) \int \psi = \dots \end{aligned}$$

Take $\psi \in C_c^\infty(\mathbb{R}^d)$ such that $\int \psi = 1$. Then:

$$T(\phi) = \int_{\mathbb{R}^d} \underbrace{T(\psi_x) - \left(\int_{\mathbb{R}^d} \sum_{i=1}^d \int_0^1 g_i(x+ty) y_i \psi(y) dt dy \right)}_{f(x)} \phi(x) dx$$

for all $\phi \in C_c^\infty$, so $T = f \in C(\Omega)$. Thus $T = f \in C(\Omega)$ and $\partial_{x_i} T = g_i \in C(\Omega)$. Then we need to prove that $f \in C^1(\Omega)$ and $\partial_{x_i} f = g_i$ (classical derivative). Since $f \in W_{loc}^{1,1}$:

$$f(x+y) - f(x) = \int_0^1 \sum_{i=1}^d g_i(x+ty) y_i dt \quad \forall x, y$$

In particular:

$$\begin{aligned} \frac{f(x+he_i) - f(x)}{h} &= \int_0^1 \frac{1}{h} \sum_{i=1}^d g_i(x+the_i) h \delta_{ij} dt \\ &= \int_0^1 g_i(x+the_i) dt \xrightarrow{h \rightarrow 0} g_i(x) \end{aligned}$$

So we get $\partial_{x_i} f(x) = g_i(x) \in C(\Omega)$ in the classical sense. So $f \in C^1(\Omega)$. \blacksquare

Definition 3.55 (Sobolev Spaces) Let $\Omega \subseteq \mathbb{R}^d$ be open. We define for $1 \leq p \leq \infty$:

$$\begin{aligned} W^{1,p}(\Omega) &= \{f \in L^p(\Omega) \mid \partial_{x_i} f \in L^p(\Omega) \forall i = 1, \dots, d\} \\ W^{k,p}(\Omega) &= \{f \in L^p(\Omega) \mid D^\alpha f \in L^p(\Omega) \forall |\alpha| \leq k\} \\ W_{loc}^{k,p}(\Omega) &= \{f \in L_{loc}^p(\Omega) \mid D^\alpha f \in L_{loc}^p(\Omega) \forall |\alpha| \leq k\} \end{aligned}$$

Theorem 3.56 (Approximation of $W_{loc}^{1,p}(\Omega)$ by $C^\infty(\Omega)$) Let $\Omega \subseteq \mathbb{R}^d$ be open, let $f \in W_{loc}^{1,p}(\Omega)$. Then there exists $\{f_n\} \subseteq C^\infty(\Omega)$ such that $f_n \rightarrow f$ in $W_{loc}^{1,p}(\Omega)$, i.e. for all $K \subseteq \Omega$ compact: $\|f_n - f\|_{L^p(K)} + \sum_{i=1}^d \|\partial_{x_i}(f_n - f)\|_{L^p(K)} \rightarrow 0$.

Proof. Case $\Omega = \mathbb{R}^d$: Take $g \in C_c^\infty$, $\int g = 1$, $g_\epsilon(x) = \epsilon^{-d} g(\epsilon^{-1}x)$. Then $g_\epsilon \star f \in C_c^\infty$. Since $f \in L_{loc}^p(\Omega)$ we have $g_\epsilon \star f \rightarrow f$ in L_{loc}^p as $\epsilon \rightarrow 0$. Moreover $\partial_{x_i}(g_\epsilon \star f) = (g_\epsilon \star \partial_{x_i} f) \xrightarrow{\epsilon \rightarrow 0} \partial_{x_i} f$ in L_{loc}^p . Then we can take $f_n = g_{\frac{1}{n}} \star f$. \blacksquare

Remark 3.57 In general, if we want to compute the distributional derivative $D^\alpha f$, then we can find $f_n \rightarrow f$ in $D'(\Omega)$ and compute $D^\alpha f_n$. Then $D^\alpha f_n \rightarrow D^\alpha f$ in $D'(\Omega)$. As an example we can compute $\nabla|f|$ with $f \in W_{loc}^{1,p}(\Omega)$.

$$(\nabla|f|)(x) = \begin{cases} \nabla f(x) & f(x) > 0 \\ -\nabla f(x) & f(x) < 0 \\ 0 & f(x) = 0 \end{cases}$$

Theorem 3.58 (Chain Rule) Let $G \in C^1(\mathbb{R}^d)$ with $|\nabla G|$ is bounded. Let $f = (f_i)_{i=1}^d \in W_{loc}^{1,p}(\Omega)$. Then $x \mapsto G(f(x)) \in W_{loc}^{1,p}(\Omega)$ and

$$\partial_{x_i} G(f) = \sum_{k=1}^d (\partial_k G)(f) \cdot \partial_{x_i} f_k \quad \text{in } D'(\Omega)$$

Moreover, if $G(0) \in L^p(\Omega)$ (i.e. either $|\Omega| < \infty$ or $G(0) = 0$), then if $f = (f_i)_{i=1}^d \in W^{1,p}(\Omega)$, then $G(f) \in W^{1,p}(\Omega)$.

Proof. Since $G \in C^1$ we have that G is bounded in any compact set. Moreover $\|\nabla G\|_{L^\infty} < \infty$ implies:

$$|G(f) - G(0)| \leq \|\nabla G\|_{L^\infty} |f| \in L^p_{loc}$$

So $G(f) \in L^p_{loc}$. Let us compute $\partial_{x_i} G(f)$. Let $\{f^{(n)}\}_{n=1}^\infty \subseteq C^\infty$ such that $f^{(n)} \rightarrow f$ in $W^{1,p}_{loc}$, then:

$$|G(f^{(n)}) - G(f)| \leq \|\nabla G\|_{L^\infty} |f^{(n)} - f| \rightarrow 0 \text{ in } L^p_{loc}$$

So $G(f^{(n)}) \rightarrow G(f)$ in L^p_{loc} , thus $\partial_{x_i} G(f^{(n)}) \rightarrow \partial_{x_i} G(f)$ in $D'(\Omega)$. On the other hand, by the standard Chain-Rule for C^1 -functions:

$$\partial_{x_i} G(f^{(k)}) = \sum_{k=1}^d \underbrace{\partial_k G(f^{(k)})}_{(\text{b.d.} \rightarrow \partial_k G(f))} \underbrace{\partial_i f_k^{(n)}}_{(\rightarrow \partial_i f_k \text{ in } L^p(\Omega))} \rightarrow \sum_{k=1}^d \partial_k G(f) \partial_i f_k \text{ in } L^p_{loc}(\Omega)$$

Thus

$$\partial_{x_i} G(f) = \sum_{k=1}^d \underbrace{\partial_k G(f)}_{\in L^\infty} \underbrace{\partial_i f_k}_{\in L^p_{loc}} \in L^p_{loc} \text{ in } D'(\Omega)$$

So $G(f) \in W^{1,p}_{loc}(\Omega)$. Assume that $G(0) \in L^p(\Omega)$ (i.e. $|\Omega| < \infty$ or $G(0) = 0$). If $f \in W^{1,p}(\Omega)$, then $G(f) \in W^{1,p}(\Omega)$ since

$$|G(f) - G(0)| \leq \|\nabla G\|_{L^\infty} |f| \in L^p \Rightarrow G(f) \in L^p$$

and

$$\partial_{x_i} G(f) = \sum_k \underbrace{\partial_k G}_{\in L^\infty} \underbrace{\partial_i f_k}_{\in L^p} \in L^p \Rightarrow G(f) \in W^{1,p}(\Omega)$$

■

Theorem 3.59 (Derivative of absolute value) Let $\Omega \subseteq \mathbb{R}^d$ be open. Let $f \in W^{1,p}(\Omega)$. Then $|f| \in W^{1,p}(\Omega)$ and if f is real-valued:

$$(\nabla |f|)(x) = \begin{cases} \nabla f(x) & f(x) > 0 \\ -\nabla f(x) & f(x) < 0 \\ 0 & f(x) = 0 \end{cases}$$

Proof. Exercise. Hint: Use the Chain-Rule for $G_\epsilon(x) = \sqrt{\epsilon^2 + x^2} - \epsilon \rightarrow |x|$ as $\epsilon \rightarrow 0$ ■

3.4 Distribution vs. measures

Let μ be a Borel measure in \mathbb{R}^d s.t. $\mu(K) < \infty$ for all compact $K \subseteq \mathbb{R}^d$. Then define

$$T : D(\mathbb{R}^d) \longrightarrow \mathbb{C}$$

$$\phi \longmapsto \int_{\mathbb{R}^d} \phi(x) d\mu(x) \quad \forall \phi \in C_c^\infty$$

\rightsquigarrow T is a distribution since if $\phi_n \rightarrow \phi$ in $D(\Omega)$, then

$$|T(\phi_n) - T(\phi)| \leq \int_{\mathbb{R}^d} |\phi_n - \phi| d\mu(x) \leq \|\phi_n - \phi\|_{L^\infty} \left(\int_K d\mu \right) \xrightarrow{n \rightarrow \infty} 0$$

Example 3.60 δ_0 in $D'(\mathbb{R}^d)$ is a Borel probability measure.

Theorem 3.61 (Positive distributions are measures) Let $\Omega \subseteq \mathbb{R}^d$ be open, let $T \in D'(\Omega)$. Assume $T \geq 0$, i.e. $T(\phi) \geq 0$ for all $\phi \in D(\Omega)$ satisfying $\phi(x) \geq 0$ for all x . Then there is a Borel positive measure μ on Ω such that $\mu(K) < \infty$ for all $K \subseteq \Omega$ compact and:

$$T(\phi) = \int_{\Omega} \phi(x) d\mu(x) \quad \forall \phi \in D(\Omega)$$

Proof. See Lieb-Loss Analysis. Sketch: If $O \subseteq \mathbb{R}^d$ is open, then

$$\mu(O) = \sup\{T(\phi) \mid \phi \in D(\Omega), 0 \leq \phi \leq 1, \text{supp } \phi \subseteq O\}$$

For all $A \subseteq \Omega$ (not necessarily open),

$$\mu(A) = \inf\{\mu(O) \mid O \text{ open}, A \subseteq O\}$$

The mapping $\mu : 2^{\Omega} \rightarrow [0, \infty]$ is an outer measure, i.e.

1. $\mu(\emptyset) = 0$
2. $\mu(A) \leq \mu(B)$ if $A \subseteq B$
3. $\mu(\bigcup_{i=1}^{\infty} A_i) \leq \sum_{i=1}^{\infty} \mu(A_i)$

From the outer measure we can find a σ -algebra Σ and μ is a measure on Σ s.t. E is measurable iff

$$\mu(E) = \mu(E \cap A) + \mu(E \cap A^c).$$

So all open sets are measurable, thus outer regularity (by def $\mu(A) = \inf\{\mu(O) \mid O \text{ open } \supseteq A\}$), so inner regularity $\mu(A) = \sup\{\mu(K) \mid K \text{ compact } \subseteq A\}$. ■

Exercise 3.62 (E 4.1) Prove that if $T_n \rightarrow T$ in $D'(\mathbb{R}^d)$, then $D^{\alpha}T_n \rightarrow D^{\alpha}T$ in $D'(\mathbb{R}^d)$ for all $\alpha \in \mathbb{N}^d$.

Exercise 3.63 (E 4.2)

Exercise 3.64 (E 4.3) $f \in L^1(\mathbb{R}^d)$, $\int f = 1$ $f_{\epsilon}(x) = \epsilon^{-d}f(\epsilon^{-1}x)$. Then $f_{\epsilon} \rightarrow \delta_0$ in $D'(\mathbb{R}^d)$.

Exercise 3.65 (E 4.4) Let $\{f_n\} \subseteq L^1$, $\text{supp } f \subseteq B(0, 1)$, $f_n \rightarrow f$ in L^1 . Prove for all $g \in C_c^{\infty}$ that $f_n \star g \rightarrow f \star g$ in $D(\mathbb{R}^d)$.

Solution. Since $f_n \in L^1$, $\text{supp } f \subseteq B(0, 1)$ and $g \in C_c^{\infty}$ we have $f_n \star g \in C_c^{\infty}$ and

$$\text{supp}(f_n \star g) \subseteq (\text{supp } g) + \overline{B(0, 1)} = K.$$

Since $f_n \rightarrow f$ in L^1 there is a subsequence $f_{n_k} \rightarrow f$ almost everywhere, so f supp in $\overline{B(0, 1)}$, so $f \star g \in C_c^{\infty}$, $\text{supp}(f \star g) \subseteq K$. We have:

$$\begin{aligned} |f_n \star g(x) - f \star g(x)| &= \left| \int_{\mathbb{R}^d} (f_n(y) - f(y))g(x-y) dy \right| \\ &\leq \int_{\mathbb{R}^d} |f_n(y) - f(y)||g(x-y)| dy \\ &\leq \|g\|_{L^{\infty}} \|f_n - f\|_{L^1} \xrightarrow{n \rightarrow \infty} 0 \end{aligned}$$

thus $\|f_n \star g - f \star g\|_{L^\infty} \rightarrow 0$. Similary:

$$\|D^\alpha(f_n \star g) - D^\alpha(f \star g)\|_{L^\infty} = \|f_n \star \underbrace{(D^\alpha g)}_{\in C_c^\infty} - f \star (D^\alpha g)\|_{L^\infty} \xrightarrow{n \rightarrow \infty} 0$$

for all $\alpha \in \mathbb{N}^d$, so $f_n \star g \rightarrow f \star g$ in $D(\mathbb{R}^d)$. ■

Exercise 3.66 (E 4.5) Compute distributional derivatives f', f'' of $f(x) = x|x-1|$.

Solution. We prove $f'(x) = g(x) := \begin{cases} 2x-1 & x > 1 \\ 1-2x & x < 1 \end{cases}$. Take $\phi \in C_c^\infty(\mathbb{R}^d)$.

$$\begin{aligned} -f'(\phi) &= -\int_{\mathbb{R}^d} f \phi' dy \\ &= -\int_{-\infty}^1 f \phi' dy - \int_1^\infty f \phi' dy \\ &= [f\phi]_{-\infty}^1 - \int_{-\infty}^1 f' \phi dy + [f\phi]_1^\infty - \int_1^\infty f' \phi dy \\ &= [f\phi]_{-\infty}^1 - \int_{-\infty}^1 g \phi dy + [f\phi]_1^\infty - \int_1^\infty g \phi dy \\ &= f(1-)\phi(1) - f(1+)\phi(1) - \int_{\mathbb{R}^d} g \phi dy \\ &= 0 - \int_{\mathbb{R}^d} g \phi dy \end{aligned}$$

Now we compute $f'' = g'$. Take $\phi \in C_c^\infty(\mathbb{R}^d)$:

$$\begin{aligned} -(g')(\phi) &= \int_{\mathbb{R}^d} g \phi' dy \\ &= \int_{-\infty}^1 g \phi' dy + \int_1^\infty g \phi' dy \\ &= [g(1-) - g(1+)]\phi(1) - \int_{-\infty}^1 g' \phi dy - \int_1^\infty g' \phi dy \\ &= [g(1-) - g(1+)]\phi(1) - \int_{-\infty}^1 (-2)\phi dy - \int_1^\infty 2\phi dy \\ &= -2\phi(1) + \int_{-\infty}^\infty [2\mathbb{1}_{(-\infty,1)}(x) - 2\mathbb{1}_{(1,\infty)}(x)]\phi(x) dx \\ &= -2\delta_1(\phi) + \int_{-\infty}^\infty [2\mathbb{1}_{(-\infty,1)}(x) - 2\mathbb{1}_{(1,\infty)}(x)]\phi(x) dx \\ &\Rightarrow g' = \underbrace{2\delta_1}_{\notin L_{loc}^1} - \underbrace{2\mathbb{1}_{(-\infty,1)} + 2\mathbb{1}_{(1,\infty)}}_{\in L_{loc}^1} \end{aligned} \quad \blacksquare$$

Chapter 4

Weak Solutions and Regularity

Definition 4.1 Consider the linear PDE:

$$\sum_{\alpha} c_{\alpha} D^{\alpha} u(x) = F(x), \quad c_{\alpha} \text{ constant, } F \text{ given}$$

A function u is called a weak solution (a distributional solution) if

$$\sum_{\alpha} c_{\alpha} D^{\alpha} u = F \quad \text{in } D'(\Omega).$$

Namely,

$$\sum_{\alpha} (-1)^{|\alpha|} c_{\alpha} \int_{\Omega} u D^{\alpha} \phi = \int_{\Omega} F \phi, \quad \forall \phi \in D(\Omega)$$

Regularity: Given some condition on the data F , what can we say about the smoothness of u ? Can we say that the equation holds in the classical sense? We derived G (the solution of the Laplace Equation) before in two ways:

1. $\Delta G(x) = 0$ for all $x \neq 0$, assuming $G(x) = G(|x|)$ and $d \geq 2$
2. $\hat{G}(k) = \frac{1}{|2\pi k|^2}$ for $d \geq 3$

Theorem 4.2 For all $d \geq 1$ we have $G \in L^1_{loc}(\mathbb{R}^d)$ and $-\Delta G = \delta_0$ in $D'(\mathbb{R}^d)$.

Proof. Take $\phi \in D(\mathbb{R}^d)$. Then:

$$\begin{aligned} (-\Delta G_y)(\phi) &= G_y(-\Delta \phi) = \int_{\mathbb{R}^d} G_y(x)(-\Delta \phi)(x) dx \\ &= \int_{\mathbb{R}^d} G(y-x)(-\Delta \phi)(x) dx \\ &= [G \star (-\Delta \phi)](y) = (-\Delta)(G \star \phi)(y) \end{aligned}$$

Recall for all $f \in C^2$, $-\Delta(G \star f) = f$ pointwise. So we can conclude $-\Delta G_y = \delta_y$ in $D'(\mathbb{R}^d)$. ■

Remark 4.3 In $d = 1$, $G(x) = -\frac{1}{2}|x|$, so $-G'(x) = \text{sgn}(x)/2$, so $-G''(x) = \delta_0$.

Remark 4.4 Formally:

$$-\Delta(G_y \star \phi) = (-\Delta G_y) \star \phi(x) = (\delta_0 \star \phi)(x) = \int_{\mathbb{R}^d} \delta_0(y) \phi(x-y) dy = \delta_0(\phi(x - \bullet))$$

Theorem 4.5 (Poisson's equation with L^1_{loc} data) Let $f \in L^1_{loc}(\mathbb{R}^d)$ s.t. $\omega_d f \in L^1(\mathbb{R}^d)$ where

$$\omega_d(x) = \begin{cases} 1 + |x| & d = 1 \\ \log(1 + |x|) & d = 2 \\ \frac{1}{1+|x|^{d-2}} & d \geq 3, \end{cases}$$

then $u(x) = (G \star f)(x) \in L^1_{loc}(\mathbb{R}^d)$. Moreover $-\Delta u = f$ in $D'(\mathbb{R}^d)$. In fact, $u \in W^{1,1}_{loc}(\mathbb{R}^d)$ and:

$$\partial_{x_i} u(x) = (\partial_{x_i} G) \star f(x) = \int_{\mathbb{R}^d} (\partial_{x_i} G)(x-y) f(y) dy$$

Remark 4.6 We can also replace \mathbb{R}^d by Ω and get $-\Delta u = f$ in $D'(\Omega)$.

Proof of Theorem 4.5. First we check that $u \in L^1_{loc}$. Take any Ball $B(0, R) \subseteq \mathbb{R}^d$, prove $\int_B |u| dy < \infty$. We have

$$\begin{aligned} \int_B |u| dy &= \int_B \left| \int_{\mathbb{R}^d} G(x-y) f(y) dy \right| dx \\ &\leq \int_B \int_{\mathbb{R}^d} |G(x-y)| |f(y)| dy dx \\ &= \int_{\mathbb{R}^d} \left(\int_B |G(x-y)| dx \right) |f(y)| dy \end{aligned}$$

If $y \notin B = B(0, R)$, then by Newton's theorem (Mean-value theorem):

$$\int_{B(0,R)} |G(x-y)| dx = |B(0, R)| |G(y)| \leq C |B| \omega_d(y)$$

If $y \in B$, then $|y| \leq R$, so $|x-y| \leq 2R$ if $x \in B$.

$$\int_{B(0,R)} |G(x-y)| dx \leq \int_{|x-y| \leq 2R} |G(x-y)| dx = \int_{|z| \leq 2R} |G(z)| dz \leq c_R$$

as $G \in L^1_{loc}$. Thus

$$\int_B |u| dy \leq c_B \int_{|y| \geq R} \omega_d(y) |f(y)| dy + c_B \int_{|y| \leq R} |f(y)| dy < \infty$$

Let us prove $-\Delta u = f$ in $D'(\mathbb{R}^d)$. Take $\phi \in D(\mathbb{R}^d)$. Then:

$$\begin{aligned}
(-\Delta u)(\phi) &= u(-\Delta \phi) \\
&= \int_{\mathbb{R}^d} u(x)(-\Delta \phi)(x) dx \\
&= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} G(x-y)f(y)(-\Delta \phi)(x) dx dy \\
&= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} G(y-x)f(y)(-\Delta \phi)(x) dx dy \\
&= \int_{\mathbb{R}^d} [G \star (-\Delta \phi)](y)f(y) dy \\
&= \int_{\mathbb{R}^d} -\Delta(G \star \phi)(y)f(y) dy \\
&= \int_{\mathbb{R}^d} \phi(y)f(y) dy
\end{aligned}$$

So $-\Delta u = f$ in $D'(\mathbb{R}^d)$. We check that $\partial_i G \star f \in L^1_{loc}(\mathbb{R}^d)$. Note that

$$|\partial_i G(x)| \leq c \frac{1}{|x|^{d-1}} \in L^1_{loc}(\mathbb{R}^d)$$

and

$$\int_{B(0,R)} |\partial_i G(x-y)| dx \leq \begin{cases} C_r \omega_d(y) & |y| \geq R \\ C_r & |y| \leq R \end{cases}$$

So $\int_{B(0,R)} |(\partial_i G \star f)(y)| dy < \infty$ for all $R > 0$. For all $\phi \in D(\mathbb{R}^d)$:

$$\begin{aligned}
-(\partial_i u)(\phi) &= u(\partial_i \phi) = \int_{\mathbb{R}^d} u(x)\partial_i \phi(x) dx \\
&= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} G(x-y)f(y)\partial_i \phi(x) dx dy \\
&= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} G(y-x)f(y)\partial_i \phi(x) dx dy \\
&= \int_{\mathbb{R}^d} (G \star \partial_i^y \phi)(y)f(y) dy \\
&= \int_{\mathbb{R}^d} (\partial_i^y G \star \phi)(y)f(y) dy \\
&= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \partial_i^y G(y-x)f(y)\phi(x) dx dy \\
&= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} -(\partial_i G)(x-y)f(y)\phi(x) dx dy \\
&= - \int_{\mathbb{R}^d} (\partial_i G \star f)(x)\phi(x) dx
\end{aligned}$$

So $\partial_i u = \partial_i G \star f \in L^1_{loc}(\mathbb{R}^d)$. Thus $u \in L^1_{loc}$, $\partial_i u \in L^1_{loc}$ for all i . So $u \in W^{1,1}_{loc}(\mathbb{R}^d)$. \blacksquare

Regularity: We consider the Laplace Equation $\Delta u = 0$ in \mathbb{R}^d .

Lemma 4.7 (Weyl) If $\Omega \subseteq \mathbb{R}^d$ open and $T \in D'(\Omega)$ s.t. $\Delta T = 0$ in $D'(\Omega)$, then: $T = f \in C^\infty(\Omega)$ and f is a harmonic function.

Proof. ($\Omega = \mathbb{R}^d$). Take $\phi \in C_c^\infty$, then $y \mapsto T(\phi_y) = T(\phi(-y))$ is C^∞ and $\Delta_y T(\phi_y) = T((\Delta\phi)_y) = (\Delta T)(\phi_y) = 0$. Take $g \in C_c^\infty$, g is radial. Then:

$$\int_{\mathbb{R}^d} T(\phi_y)g(y) dy \stackrel{(\text{exercise})}{=} \int_{\mathbb{R}^d} T(\phi)g(y) dy = T(\phi) \left(\int_{\mathbb{R}^d} g dy \right)$$

Exercise 4.8 Let $f \in C^\infty(\mathbb{R}^d)$ be a harmonic function and $g \in C_c^\infty$, g is radial. Then:

$$\int_{\mathbb{R}^d} f(x)g(x) dx = f(0) \left(\int_{\mathbb{R}^d} g(x) dx \right)$$

On the other hand:

$$\int_{\mathbb{R}^d} T(\phi_y)g(y) dy = T(\phi \star g) = T(g \star \phi) = \int_{\mathbb{R}^d} T(g_y)\phi(y) dy$$

Take $\int_{\mathbb{R}^d} g dy = 1$, then:

$$T(\phi) = \int_{\mathbb{R}^d} T(g_y)\phi(y) dy$$

For all $\phi \in C_c^\infty$. Then $T = T(g_y) \in C^\infty$ ■

Now let's regard the Poisson Equation $-\Delta u = f$ in $D'(\mathbb{R}^d)$.

Remark 4.9 Any solution has the form $u = G \star g + h$ where $\Delta h = 0$ in $D'(\mathbb{R}^d)$. By Weyl's Lemma (4.7), $h \in C^\infty$, then we only need to consider the regularity of $G \star f$.

Remark 4.10 The regularity is a *local question*, namely if we write

$$f = f_1 + f_2 = f\phi + f(1 - \phi),$$

where $\phi = 1$ in a ball B and $\phi \in C_c^\infty$.

Then $G \star f = G \star f_1 + G \star f_2$. Here $f_2 = f(1 - \phi) = 0$ in B . With Weyl's Lemma (4.7), $G \star f_2 \in C^\infty$.

Theorem 4.11 (Low Regularity of Poisson Equation) Let $f \in L^p(\mathbb{R}^d)$ and compactly supported. Then

a) If $p \geq 1$, then

- $G \star f \in C^1(\mathbb{R}^d)$ if $d = 1$.
- $G \star f \in L_{loc}^q(\mathbb{R}^d)$ for any $q < \infty$ if $d = 2$.
- $G \star f \in L_{loc}^q(\mathbb{R}^d)$ for $q < \frac{d}{d-2}$ if $d \geq 3$.

b) If $\frac{d}{2} < p \leq d$, then $G \star f \in C_{loc}^{0,\alpha}(\mathbb{R}^d)$ for all $0 < \alpha < 2 - \frac{d}{p}$, i.e.

$$|(G \star f)(x) - (G \star f)(y)| \leq C_k |x - y|^\alpha \quad \forall x, y \in K$$

with K compact in \mathbb{R}^d .

c) If $p > d$, then $G \star f \in C_{loc}^{1,\alpha}(\mathbb{R}^d)$ for all $0 < \alpha < 1 - \frac{d}{p}$.

where G is den fundamental solution of the laplace equation.

Example 4.12 Let $r = |x|$

$$u(x) = \omega(r) = \log(|\log(r)|)$$

if $0 < r < \frac{1}{2}$, so u is well-defined in $B = B(0, \frac{1}{2})$. We conclude:

$$-\Delta_{\mathbb{R}^3} u(x) = -\omega''(r) - \frac{2\omega'(r)}{r} = f(x) \in L^{\frac{3}{2}}(B)$$

But the Theorem (b) tells us that if $f \in L^{\frac{3}{2}}$ then u is continuous but $u \notin C(B)$.

Proof of theorem 4.11. a) ($p = 1$) Why is $G \star f \in L_{loc}^q$? Recall from the proof of Youngs inequality:

$$\begin{aligned} |(G \star f)(x)| &= \left| \int_{\mathbb{R}^d} G(x-y) f(y) dy \right| \\ (\text{H\"older}) &= \left(\int_{\mathbb{R}^d} |G(x-y)|^q |f(y)| dy \right)^{\frac{1}{q}} \left(\int_{\mathbb{R}^d} |f(y)| dy \right)^{\frac{1}{q'}} \end{aligned}$$

Where $\frac{1}{q} + \frac{1}{q'} = 1$. Then:

$$|(G \star f)(x)|^q \leq C \int_{\mathbb{R}^d} |G(x-y)|^q |f(y)| dy$$

For any Ball $B = B(0, R) \subseteq \mathbb{R}^d$:

$$\begin{aligned} \int_B |G \star f(x)|^q dx &\leq C \int_B \left(\int_{\mathbb{R}^d} |G(x-y)|^q |f(y)| dy \right) dx \\ &= C \int_{\mathbb{R}^d} \left(\int_B |G(x-y)|^q dx \right) |f(y)| dy \end{aligned}$$

$G(x) \sim \frac{1}{|x|^{\frac{1}{d-2}}} \rightsquigarrow |G|^q = \frac{1}{|x|^{\frac{1}{(d-2)q}}} \in L_{loc}^1(\mathbb{R}^d)$ if $(d-2)q < 2 \Leftrightarrow q < \frac{d}{d-2}$. Here, $y \in \text{supp } f$, so $|y| \leq R_1$, then $|x-y| \leq R+R_1$ if $|x| \leq R$. With $y \in \text{supp } f$, this implies:

$$\int_{B(0,R)} |G(x-y)|^q dx \leq \int_{|z| \leq R+R_1} |G(z)|^q dz < \infty$$

b)

$$(G \star f)(x) - (G \star f)(y) = \int_{\mathbb{R}^d} (G(x-z) - G(y-z)) f(z) dz$$

So

$$|G \star f(x) - (G \star f)(y)| \leq C \int_{\mathbb{R}^d} \left| \frac{1}{|x-z|^{d-2}} - \frac{1}{|y-z|^{d-2}} \right| |f(z)| dz$$

for all $x, y \in \mathbb{R}^d$:

$$\begin{aligned} \left| \frac{1}{|x|^{d-2}} - \frac{1}{|y|^{d-2}} \right| &= \left| \left(\frac{1}{|x|} - \frac{1}{|y|} \right) \left(\frac{1}{|x|^{d-3}} + \dots + \frac{1}{|y|^{d-3}} \right) \right| \\ &\leq C \frac{||x| - |y||}{|x||y|} \max \left(\frac{1}{|x|^{d-3}}, \frac{1}{|y|^{d-3}} \right) \\ &= C \frac{|x-y|}{|x||y|} \max \left(\frac{1}{|x|^{d-3}}, \frac{1}{|y|^{d-3}} \right) \\ &\leq C \max(|x|, |y|)^{1-\alpha} \frac{|x-y|^\alpha}{|x||y|} \max \left(\frac{1}{|x|^{d-3}}, \frac{1}{|y|^{d-3}} \right) \end{aligned}$$

as

$$||x| - |y|| \leq \min(|x - y|, \max(|x|, |y|)) \leq |x - y|^\alpha \max(|x|, |y|)^{1-\alpha}$$

Thus, for all $x, y \in \mathbb{R}^d$:

$$\begin{aligned} \left| \frac{1}{|x|^{d-2}} - \frac{1}{|y|^{d-2}} \right| &\leq C|x - y|^\alpha \frac{\max(|x|, |y|)^{1-\alpha}}{|x||y|} \max\left(\frac{1}{|x|^{d-3}}, \frac{1}{|y|^{d-3}}\right) \\ &\leq C|x - y|^\alpha \max\left(\frac{1}{|x|^{d-2+\alpha}}, \frac{1}{|y|^{d-2+\alpha}}\right) \end{aligned}$$

So we get

$$\left| \frac{1}{|x - y|^{d-2}} - \frac{1}{|y - z|^{d-2}} \right| \leq C|x - y|^\alpha \max\left(\frac{1}{|x - z|^{d-2+\alpha}}, \frac{1}{|y - z|^{d-2+\alpha}}\right)$$

Therefore:

$$\begin{aligned} &|G \star f(x) - G \star f(y)| \\ &\leq C \int_{\mathbb{R}^d} |x - y|^\alpha \max\left(\frac{1}{|x - z|^{d-2+\alpha}}, \frac{1}{|y - z|^{d-2+\alpha}}\right) |f(z)| dz \\ &\leq C|x - y|^\alpha \left(\sup_{\xi \in \mathbb{R}^d} \int_{\mathbb{R}^d} \frac{1}{|\xi - z|^{d-2+\alpha}} |f(z)| dz \right) \end{aligned}$$

Claim: If $f \in L^p(\mathbb{R}^d)$ is compactly supported, $d \geq p > \frac{d}{2}$, then:

$$\sup_{\xi \in \mathbb{R}^d} \int_{\mathbb{R}^d} \frac{1}{|\xi - z|^{d-2+\alpha}} |f(z)| dz < \infty$$

for all $0 < \alpha < 2 - \frac{d}{p}$. Assume $\text{supp } f \subseteq \overline{B(0, R_1)}$. Consider 2 cases:

- If $|\xi| > 2R_1$, then: $|\xi - z| \geq R_1$ for all $z \in B(0, R_1)$. Hence:

$$\int_{\mathbb{R}^d} \frac{1}{|\xi - z|^{d-2+\alpha}} |f(z)| dz \leq \frac{1}{R_1^{d-2+\alpha}} \|f\|_{L^1} < \infty$$

- If $|\xi| \leq 2R_1$, then: $|\xi - z| \leq 3R_1$ for all $z \in B(0, R_1)$:

$$\begin{aligned} \int_{\mathbb{R}^d} \frac{1}{|\xi - z|^{d-2+\alpha}} |f(z)| dz &\leq \int_{|\xi - z| \leq 3R_1} \frac{1}{|\xi - z|^{d-2+\alpha}} |f(z)| dz \\ \text{(H\"older)}, \left(\frac{1}{p} + \frac{1}{q} = 1\right) &\leq \left(\int_{\mathbb{R}^d} |f(z)|^p dz \right)^{\frac{1}{p}} \\ &\quad \cdot \left(\int_{|\xi - z| \leq 3R_1} \frac{1}{|\xi - z|^{(d-2+\alpha)q}} dz \right)^{\frac{1}{q}} \\ &= \|f\|_{L^p} \left(\int_{|z| \leq 3R_1} \frac{1}{|z|^{(d-2+\alpha)q}} dz \right)^{\frac{1}{q}} < \infty \end{aligned}$$

c) ($d \geq 3$) We already know:

$$\partial_i(G \star f) = (\partial_i G \star f) \in L_{loc}^1(\mathbb{R}^d)$$

as $\omega_d f \in L^1(\mathbb{R}^d)$. We claim that $\partial_i G \star f \in C^{0,\alpha}(\mathbb{R}^d)$. So $G \star f \in C^{1,\alpha}(\mathbb{R}^d)$ by the equivalence between the classical and the distributional derivatives. Exercise. Hint:

$$|\partial_i G \star f(x) - \partial_i G \star f(y)| \leq \int_{\mathbb{R}^d} |\partial_i G(x-z) - \partial_i G(y-z)| |f(z)| dz,$$

$$\partial_i G(x) = \frac{-x_i}{d|B_1||x|^d} \rightsquigarrow \text{Need to estimate } |\partial_i G(x) - \partial_i G(y)| \leq C|x-y|^\alpha. \quad \blacksquare$$

Theorem 4.13 (High regularity for Poisson's equation) Let $f \in C^{0,\alpha}(\mathbb{R}^d)$, $0 < \alpha < 1$ be compactly supported. Then $G \star f \in C^{2,\alpha}(\mathbb{R}^d)$.

Remark 4.14 $(-\Delta u = f)$ and $f \in C(\mathbb{R}^d)$ does not imply that $u \in C^2(\mathbb{R}^d)$. (exercise)

Remark 4.15 If $f \in C^{k,\alpha}(\mathbb{R}^d)$, $k \in \{0, 1, \dots\}$, $0 < \alpha < 1$ is compactly supported, then $G \star f \in C^{k+2,\alpha}(\mathbb{R}^d)$. This more general statement is a consequence of the theorem since

$$D^\beta(G \star f) = G \star \underbrace{(D^\beta f)}_{\in C^{0,\alpha}}$$

for all $\beta = (\beta_1, \dots, \beta_d)$, $|\beta| \leq k$.

Proof of theorem 4.13. Since $f \in L^p$ for all $p \leq \infty$ by the low regularity (4.11) we have $G \star f \in C^{1,\alpha}$ and $\partial_i(G \star f) = \partial_i G \star f$ in the classical sense. We will compute the distributional derivatives $\partial_i \partial_j(G \star f)$ and prove that they are Hölder continuous. Compute $\partial_j \partial_i(G \star f)$: For all $\phi \in C_c^\infty(\mathbb{R}^d)$ we have

$$\begin{aligned} -(\partial_j \partial_i G \star f)(\phi) &= (\underbrace{\partial_i(G \star f)}_{\in C})(\partial_j \phi) \\ &= \int_{\mathbb{R}^d} ((\partial_i G) \star f)(x) \partial_j \phi(x) dx \\ &= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \partial_i G(x-y) f(y) \partial_j \phi(x) dx dy \\ &= \int_{\mathbb{R}^d} f(y) \left[\int_{\mathbb{R}^d} \partial_i G(x-y) \partial_j \phi(x) dx \right] dy \\ &\stackrel{?}{=} \int_{\mathbb{R}^d} \square \phi(y) dy \end{aligned}$$

Recall: $\partial_i G(x) = \frac{-x_i}{d|B_1||x|^d}$, $\partial_i \partial_j G(x) = \frac{1}{|B_1|} \left[\frac{x_i x_j}{|x|^2} - \frac{\delta_{ij}}{d} \right] \frac{1}{|x|^d}$. We have:

$$\int_{\mathbb{R}^d} \partial_i G(x-y) \partial_j \phi(x) dx = \lim_{\epsilon \rightarrow 0^+} \int_{|x-y| \geq \epsilon} \partial_i G(x-y) \partial_j \phi(x) dx$$

By dominated convergence we have $|\partial_i G(x-y) \partial_j \phi(x)| \in L^1(dx)$. By the Gauss-Green-Theorem (2.2) for all $\epsilon > 0$:

$$\begin{aligned} &\int_{|x-y| \geq \epsilon} \partial_i G(x-y) \partial_j \phi(x) dx \\ &= \int_{\partial B(y,\epsilon)} \partial_i G(x-y) \phi(x) \omega_j dS(x) - \int_{|x-y| \geq \epsilon} \partial_j \partial_i G(x-y) \phi(x) dx \end{aligned}$$

Where $\omega = \frac{x-y}{|x-y|}$. For the boundary term:

$$\begin{aligned}
- \int_{\partial B(y, \epsilon)} \partial_i G(x-y) \phi(x) \omega_j dS(x) &= -\epsilon^{d-1} \int_{\partial B(0,1)} \partial_i G(\epsilon \omega) \phi(y + \epsilon \omega) \omega_j d\omega \\
(\star) \quad &= \int_{\partial B(0,1)} \frac{1}{d|B_1|} \omega_i \omega_j \phi(y + \epsilon \omega) d\omega \\
&\xrightarrow{\epsilon \rightarrow 0} \int_{\partial B(0,1)} \frac{1}{d|B_1|} \omega_i \omega_j \phi(y) d\omega \\
&= \frac{1}{d} \delta_{i,j} \phi(y)
\end{aligned}$$

(\star) $\partial_i G(x) = \frac{-x_i}{d|B_1||x|^d}$, so $\partial_i G(\epsilon \omega) = -\frac{-\omega_i}{d|B_1|} \frac{1}{\epsilon^{d-1}}$. for all $|\omega| = 1$.

Now we split:

$$\begin{aligned}
&- \int_{|x-y| \geq \epsilon} \partial_i \partial_j G(x-y) \phi(x) dx \\
&= - \int_{|x-y| \geq 1} \partial_i \partial_j G(x-y) \phi(x) dx - \int_{1 \geq |x-y| \geq \epsilon} \partial_i \partial_j G(x-y) \phi(x) dx
\end{aligned}$$

The key observation is: $\int_{\partial B(0,r)} \partial_i \partial_j G(x) dx = 0$ since

$$\partial_i \partial_j G(x) = \frac{1}{|B_1|} \left(\omega_i \omega_j - \frac{\partial_{ij}}{d} \right) \frac{1}{|x|^d},$$

$\omega = \frac{x}{|x|}$. For example if $i = 1, j = 2, r = 1$:

$$\int_{\partial B(0,1)} \partial_1 \partial_2 G(x) dS(x) = \frac{1}{|B_1|} \int_{\partial B(0,1)} \omega_1 \omega_2 d\omega,$$

$\partial B(0,1) = \{\omega \mid |\omega| = 1\}$. Consider: $\omega \mapsto R\omega, (\omega_1, \dots, \omega_d) \mapsto (-\omega_1, \omega_2, \dots, \omega_d)$. Then

$$- \int_{1 \geq |x-y| \geq \epsilon} \partial_i \partial_j G(x-y) \phi(y) dx = 0.$$

So

$$- \int_{1 \geq |x-y| \geq \epsilon} \partial_i \partial_j G(x-y) \phi(x) dx = - \int_{1 \geq |x-y| \geq \epsilon} \partial_i \partial_j G(x-y) (\phi(x) - \phi(y)) dx$$

In summary:

$$\begin{aligned}
\partial_i \partial_j (G \star f)(\phi) &= \int_{\mathbb{R}^d} f(y) \left(\int_{\mathbb{R}^d} \partial_i G(x-y) \partial_j \phi(x) dx \right) dy \\
&= \int_{\mathbb{R}^d} f(y) \frac{1}{d} \partial_{ij} \phi(y) dy \\
&\quad - \int_{\mathbb{R}^d} f(y) \left(\int_{|x-y| > 1} \partial_i \partial_j G(x-y) \phi(x) dx \right) \\
&\quad - \int_{\mathbb{R}^d} \left[\lim_{\epsilon \rightarrow 0} \int_{1 \geq |x-y| \geq \epsilon} \underbrace{\partial_i \partial_j G(x-y) (\phi(x) - \phi(y)) dx}_{\leq \frac{C}{|x-y|^d} |x-y| \|\nabla \phi\|_{L^\infty} \leq \frac{C}{|x-y|^{d-1}} \in L^1_{loc}(dx) \forall y} \right] dy \\
&= \int_{\mathbb{R}^d} \frac{\delta_{ij}}{d} f(x) \phi(x) dx - \int_{\mathbb{R}^d} \phi(x) \left(\int_{|x-y| > 1} \partial_i \partial_j G(x-y) f(y) dy \right) dx \\
&\quad - \int_{\mathbb{R}^d} \phi(x) \left[\int_{|x-y| \leq 1} \partial_i \partial_j G(x-y) (f(y) - f(x)) dy \right] dx
\end{aligned}$$

Conclusion:

$$\begin{aligned}\partial_i \partial_j (G \star f)(x) &= -\frac{\delta_{ij}}{d} f(x) + \int_{|x-y|>1} \partial_i \partial_j G(x-y) f(y) dy \\ &\quad + \int_{|x-y| \leq 1} \partial_i \partial_j G(x-y) (f(y) - f(x)) dy\end{aligned}$$

The first term $f \in C^{0,\alpha}$. The second term is also at least $C^{0,\alpha}$ since $\partial_i \partial_j G(x)$ is smooth as $|x| > 1$. We need to prove that the third term

$$W_{ij}(x) = \int_{|x-y| \leq 1} \partial_i \partial_j G(x-y) (f(y) - f(x)) dy$$

is Hölder-continuous, $|W_{ij}(x) - W_{ij}(y)| \leq C|x-y|^\alpha$. Recall:

$$|\partial_i \partial_j G(x-y) (f(y) - f(x))| \leq C \frac{1}{|x-y|^d} |x-y|^\alpha = \frac{C}{|x-y|^{d-\alpha}} \in L^1_{loc}(dy)$$

We write

$$\begin{aligned}W_{ij}(x) &= \int_{|x-y| \leq 1} \partial_i \partial_j G(x-y) (f(y) - f(x)) dy \\ &= \int_{|z| \leq 1} \partial_i \partial_j G(z) (f(x+z) - f(x)) dz\end{aligned}$$

So we get:

$$W_{ij} - W_{ij}(y) = \int_{|z| \leq 1} \partial_i \partial_j G(z) (f(x+z) - f(y+z) - f(x) + f(y)) dz$$

Easy thought: Use $|\partial_i \partial_j G(z)| \leq \frac{C}{|z|^d}$ and

$$\begin{aligned}&|f(x+z) - f(y+z) - f(x) + f(y)| \\ &\leq \begin{cases} |f(x+z) - f(x)| + |f(y+z) - f(y)| \leq C|z|^\alpha \\ |f(x+z) - f(y+z)| + |f(x) - f(y)| \leq C|x-y|^\alpha \end{cases}\end{aligned}$$

Thus:

$$\begin{aligned}|W_{ij}(x) - W_{ij}(y)| &\leq C \int_{|z| \leq 1} \frac{1}{|z|^d} \min(|z|^\alpha, |x-y|^\alpha) dz \\ &\leq C \int_{|z| \leq 1} \frac{1}{|z|^d} (|z|^\alpha)^\epsilon (|x-y|^\alpha)^{1-\epsilon}, \quad 0 < \epsilon < 1 \\ &\leq C \left(\int_{|z| \leq 1} \frac{1}{|z|^{d-\alpha\epsilon}} \right) |x-y|^{\alpha(1-\epsilon)} \\ &\leq C_\epsilon |x-y|^{\alpha(1-\epsilon)}\end{aligned}$$

thus it is easy to prove $|W_{ij}(x) - W_{ij}(y)| \leq C_\alpha |x-y|^\alpha$ for all $\alpha' \leq \alpha$. However, to get $\alpha' = \alpha$ we need a more precise estimate. We split:

$$W_{ij}(x) - W_{ij}(y) = \int_{|z| \leq 1} \dots = \int_{|z| \leq \min(4|x-y|, 1)} + \int_{4|x-y| < |z| \leq 1}$$

For the first domain:

$$\begin{aligned} & \int_{|z| \leq 4|x-y|} |\partial_{ij} G(z)| |f(x+z) - f(y+z) - f(y) + f(x)| dz \\ & \leq C \int_{|z| \leq 4|x-y|} \frac{1}{|z|^d} |z|^\alpha dz = \text{const} \cdot |x-y|^\alpha \end{aligned}$$

For the second domain:

$$\begin{aligned} & \int_{4|x-y| < |z| \leq 1} \partial_{ij} G(z) (f(x+z) - f(y+z) + f(y)f(x)) dz \\ & = \int_{4|x-y| < |z| \leq 1} \partial_{ij} G(z) (f(x+z) - f(y+z)) dz = (\dots) \end{aligned}$$

since $\int_{4|x-y| < |z| \leq 1} \partial_{ij} G(z) dz = 0$. Then

$$(\dots) = \int_{4|x-y| < |z-x| \leq 1} \partial_{ij} G(z-x) f(z) dz - \int_{4|x-y| < |z-y| \leq 1} \partial_{ij} G(z-y) f(z) dz.$$

Denote $A = \{z \mid 4|x-y| < |z-x| \leq 1\}$, $B = \{z \mid 4|x-y| < |z-y| \leq 1\}$. Consider

$$\begin{aligned} & \int_A \partial_{ij} G(z-x) f(z) dz - \int_B \partial_{ij} G(z-y) f(z) dz \\ & = \int_{A \setminus B} + \int_{B \setminus A} + \int_{A \cap B} (\partial_{ij} G(z-x) - \partial_{ij} G(z-y)) f(z) dz \end{aligned}$$

Lets regard the intersection. We have

$$\begin{aligned} \partial_{ij} G(x) &= \frac{1}{|B_1|} \frac{1}{|x|^d} (\omega_i \omega_j - \frac{1}{d} \delta_{ij}) \\ |\partial_{ij} G(x) - \partial_{ij} G(y)| &\leq C|x-y| \left(\frac{1}{|x|^{d+1}} + \frac{1}{|y|^{d+1}} \right) \end{aligned}$$

Now,

$$|\partial_{ij} G(z-x) - \partial_{ij} G(z-y)| \leq C|x-y| \left(\frac{1}{|z-x|^{d+1}} + \frac{1}{|z-y|^{d+1}} \right)$$

So we have

$$\begin{aligned} & \left| \int_{A \cap B} (\partial_{ij} G(z-x) - \partial_{ij} G(z-y)) f(z) dz \right| \\ & \leq C \int_{A \cap B} |x-y| \left(\frac{1}{|z-x|^{d+1}} + \frac{1}{|z-y|^{d+1}} \right) |f(z)| dz = (\dots) \end{aligned}$$

Now we replace $f(z)$ by $f(z) - f(x)$, then:

$$\begin{aligned} & \left| \int_{A \cap B} (\partial_{ij} G(z-x) - \partial_{ij} G(z-y)) (f(z) - f(x)) dz \right| \\ & \leq C \int_{A \cap B} |x-y| \left(\frac{1}{|z-x|^{d+1}} + \frac{1}{|z-y|^{d+1}} \right) |z-x|^\alpha dz \\ & = C \underbrace{\int_{A \cap B} |x-y| \frac{1}{|z-x|^{d+1-\alpha}} dz}_{(I)} + C \underbrace{\int_{A \cap B} |x-y| \frac{1}{|z-y|^{d+1}} |z-x|^\alpha dz}_{(II)} \end{aligned}$$

Now,

$$\begin{aligned}
(I) &\leq C|x-y| \int_{4|x-y| < |z-x| \leq 1} \frac{1}{|z-x|^{d+1-\alpha}} dz \\
&= C|x-y| \int_{4|x-y| < |z| \leq 1} \frac{1}{|z|^{d+1-\alpha}} dz \\
&\leq C|x-y| \int_{4|x-y|}^1 \frac{1}{r^{d+1-\alpha}} r^{d-1} dr \\
&= C|x-y| \int_{4|x-y|}^1 \frac{1}{r^{2-\alpha}} dr \\
&\leq C|x-y| \left[-1 + \frac{1}{(4|x-y|)^{1-\alpha}} \right] \\
&\leq C|x-y|^\alpha
\end{aligned}$$

$$\begin{aligned}
(II) &\leq C|x-y| \int_{A \cap B} \frac{1}{|z-y|^{d+1}} |z-x|^\alpha dz \\
&\leq C|x-y| \int_{A \cap B} \frac{1}{|z-y|^{d+1}} (|z-y|^\alpha + |x-y|^\alpha) dz \\
&\leq C|x-y| \underbrace{\int_B \frac{1}{|z-y|^{d+1-\alpha}} dz}_{\text{similar to (I)}} + C|x-y|^{1+\alpha} \int_B \frac{1}{|z-y|^{d+1}} dz
\end{aligned}$$

and

$$C|x-y|^{1+\alpha} \int_B \frac{1}{|z-y|^{d+1}} dz \leq \int_{4|x-y|}^1 \frac{1}{r^{d+1}} r^{d-1} dr \leq \frac{C}{|x-y|}$$

Consider $A \setminus B$:

$$\left| \int_{A \setminus B} \right| \leq C \|f\|_{L^\infty} \int_{A \setminus B} \frac{1}{|z-x|^d} dz$$

where

$$\begin{aligned}
A &= \{z \mid 4|x-y| < |z-x| \leq 1\} \\
B &= \{z \mid 4|x-y| < |z-y| \leq 1\} \\
A \setminus B &= \{z \in A \mid |z-y| \leq 4|x-y|\} \cup \{z \in A \mid |z-y| > 1\} = E_1 \cup E_2
\end{aligned}$$

for

$$\begin{aligned}
E_1 &= \{z \mid |z-y| \leq 4|x-y| < |z-x| \leq 1\} \\
&\subseteq \{z \mid 4|x-y| \leq |x-z| \leq 5|x-y|\}.
\end{aligned}$$

$|x - z| \leq |x - y| + |y - z| \leq 5|x - y|$ in E_1 . We have

$$\begin{aligned}
\int_{E_1} \frac{1}{|z - x|^d} dz &\leq \int_{4|x-y| \leq |x-z| \leq 5|x-y|} \frac{1}{|z - x|^{d-\alpha}} dz \\
&= \int_{4|x-y| \leq |z| \leq 5|x-y|} \frac{1}{|z|^{d-\alpha}} dz \\
&= \int_{4|x-y|} \frac{1}{r^d} r^{d-1} dr \\
&= \int_{4|x-y|} \frac{1}{r^{1-\alpha}} dr \\
&\leq C|x - y|^\alpha
\end{aligned}$$

Now in E_2 : $|z - x| \geq |z - y| - |y - x| \geq 1 - |y - x|$.

$$\begin{aligned}
\int_{E_2} \frac{1}{|z - x|^{d-\alpha}} dz &\leq \int \frac{1}{|z - x|^{d-\alpha}} dz = \int_{1-|x-y|}^1 \frac{1}{r^{d-\alpha}} r^{d-1} dr \\
&\leq \text{const.} \left| 1 - \frac{1}{(1 - |x - y|)^\alpha} \right| \leq C|x - y|^\alpha
\end{aligned}$$

■

Exercise 4.16 (E 5.1) Prove that if f is a harmonic function in \mathbb{R}^d and $g \in C_c(\mathbb{R}^d)$ is radial, then

$$\int_{\mathbb{R}^d} f(x)g(x) dx = f(0) \int_{\mathbb{R}^d} g(x) dx$$

Solution. $x = r\omega, r > 0, |\omega| = 1$

$$\begin{aligned}
\int_{\mathbb{R}^d} f(x)g(x) dx &\stackrel{(\text{Polar})}{=} \int_0^\infty \left(\int_{\partial B(0,1)} f(r\omega)g(r\omega) d\omega \right) dr \\
&= \int_0^\infty \left(g_0(r) \int_{\partial B(0,1)} f(r\omega) d\omega \right) dr \\
(\text{Mean value theorem (2.12)}) \quad &= \int_0^\infty \left(g_0(r) f(0) \int_{\partial B(0,1)} d\omega \right) dr \\
&= f(0) \int_0^\infty \left(\int_{\partial B(0,1)} g(r\omega) d\omega \right) dr \\
&= f(0) \int_{\mathbb{R}^d} g(x) dx
\end{aligned}$$

■

Remark 4.17 Let $g \in C_c(\mathbb{R}^d)$ be radial. Why is $\int_{\mathbb{R}^3} \frac{g(x)}{|x|} dx \neq \infty$? Because $f(x) = \frac{1}{|x|}$ is harmonic in $\mathbb{R}^d \setminus \{0\}$ and sub-harmonic in \mathbb{R}^d , $-\Delta f = c\delta_0$.

Exercise 4.18 (E 5.2) Let $1 \leq p < \infty$. Let $\Omega \subseteq \mathbb{R}^d$ be open. Consider the Sobolev Space

$$W^{1,p}(\Omega) = \{f \in L^p(\Omega) \mid \partial_{x_i} f \in L^p(\Omega), \forall i = 1, 2, \dots, d\}$$

with the norm

$$\|f\|_{W^{1,p}} = \|f\| + \sum_{i=1}^d \|\partial_{x_i} f\|_{L^p(\Omega)}.$$

Prove that $W^{1,p}(\Omega)$ is a Banach space. Here $x = (x_i)_{i=1}^d \in \mathbb{R}^d$. Hint: You can use the fact that $L^p(\Omega)$ is a Banach Space.

Solution. $W^{1,p}(\Omega) \subseteq L^p(\Omega) \times L^p(\Omega) \cdots \times L^p(\Omega) = (L^p(\Omega))^{d+1}$. For an element $f \in W^{1,p}(\Omega)$ we can think of it as $f \mapsto (f, \partial_1 f, \partial_2 f, \dots, \partial_d f)$, so $W^{1,p}(\Omega)$ is a subspace of $(L^p(\Omega))^{d+1}$, which is a norm-space. Why is $W^{1,p}(\Omega)$ closed in $(L^p(\Omega))^{d+1}$? Take $\{f_n\}_{n=1}^\infty \subseteq W^{1,p}(\Omega)$ such that $f_n \rightarrow f$ in L^p and $\partial_i f_n \rightarrow g_i$ in L^p for all $i = 1, \dots, d$. We prove that $(f, g_1, \dots, g_d) \in W^{1,p}(\Omega)$, i.e. $f \in W^{1,p}$ and $g_i = \partial_i f$ for all $i = 1, \dots, d$. We know that $f_n \rightarrow f$ in $L^p(\Omega)$, so $f_n \rightarrow f$ in $D'(\Omega)$ and $\partial_i f_n \rightarrow \partial_i f$ in $D'(\Omega)$. On the other hand we have $\partial_i f_n \rightarrow g_i$ in $L^p(\Omega)$, so $\partial_i f_n \rightarrow g_i$ in $D'(\Omega)$. So we get $\partial_i f = g_i \in L^p(\Omega)$ for all $i = 1, \dots, d$ in $D'(\Omega)$. So we can conclude $f \in W^{1,p}(\Omega)$ and $\partial_i f = g_i$ for all $i = 1, \dots, d$. ■

Exercise 4.19 (E 5.3) Let f be a real-valued function in $W^{1,p}(\mathbb{R}^d)$ for some $1 \leq p < \infty$. Prove that $|f| \in W^{1,p}(\mathbb{R}^d)$ and

$$(\nabla|f|)(x) = \begin{cases} \nabla f(x) & f(x) > 0 \\ -\nabla f(x) & f(x) < 0 \\ 0 & f(x) = 0 \end{cases}.$$

Solution. Consider $G_\epsilon(t) = \sqrt{\epsilon^2 + t^2} - \epsilon$ for $\epsilon > 0, t \in \mathbb{R}$. Clearly we have $G_\epsilon(t) \rightarrow |t|$ as $\epsilon \rightarrow 0$ and

$$G'_\epsilon(t) = \frac{2t}{2\sqrt{\epsilon^2 + t^2}} = \frac{t}{\sqrt{\epsilon^2 + t^2}},$$

so $|G'_\epsilon(t)| \leq 1$, $G_\epsilon(0) = 0$. By the chain rule, $G_\epsilon(f) \in W^{1,p}(\mathbb{R}^d)$ and

$$(\partial_i G_\epsilon(f))(x) = G'_\epsilon(f) \partial_i f(x) = \frac{f(x)}{\sqrt{\epsilon^2 + f^2(x)}} \partial_i f(x) \in L^p(\mathbb{R}^d)$$

for all $i = 1, \dots, d$. Note then when $\epsilon \rightarrow 0$ that $G_\epsilon(f)(x) \rightarrow |f(x)|$ pointwise, so $G_\epsilon(f) \rightarrow |f|$ in $L^p(\mathbb{R}^d)$. $|G_\epsilon(f)(x) - G_\epsilon(0)| \leq |f(x)| \in L^p(\mathbb{R}^d)$ by dominated convergence.

$$\partial_i G_\epsilon(f)(x) = \frac{f(x)}{\sqrt{\epsilon^2 + f^2(x)}} \partial_i f(x) \xrightarrow{\epsilon \rightarrow 0} g_i(x) := \begin{cases} \partial_i f(x) & f(x) > 0 \\ -\partial_i f(x) & f(x) < 0 \\ 0 & f(x) = 0 \end{cases}$$

$$|\partial_i G_\epsilon(f)(x)| \leq \left| \frac{f(x)}{\sqrt{\epsilon^2 + f^2(x)}} \right| |\partial_i f(x)| \leq |\partial_i f(x)| \in L^p(\mathbb{R}^d)$$

So we get $\partial_i G_\epsilon(f) \xrightarrow{\epsilon \rightarrow 0} g_i$ in $L^p(\mathbb{R}^d)$ by Dominated Convergence. So we conclude: $\partial_i(|f|) = g_i \in L^p(\mathbb{R}^d)$ for all $i = 1, \dots, d$, so $|f| \in W^{1,p}(\mathbb{R}^d)$, $|f| \in L^p$. ■

Exercise 4.20 (E 5.4) Let $\Omega \subseteq \mathbb{R}^d$ be open and bounded, $f \in L^1(\Omega)$,

$$u(x) = \int_{\Omega} G(x-y) f(y) dy$$

Let $-\Delta u = f$ in $D'(\Omega)$, $u \in L^1_{loc}(\Omega)$, $f \in L^1_{loc}(\mathbb{R}^d)$ and $\omega_d f \in L^1(\mathbb{R}^d)$, where

$$\omega_d(x) = \begin{cases} 1 + |x| & d = 1 \\ \log(1 + |x|) & d = 2 \\ \frac{1}{(1+|x|)^{d-2}} & d \geq 3 \end{cases}.$$

Prove that

$$G \star f = \int_{\mathbb{R}^d} G(x-y)f(y) dy \in L^1_{loc}(\mathbb{R}^d)$$

and $-\Delta(G \star f) = f$ in $D'(\mathbb{R}^d)$.

Solution. Define $\tilde{f} = \mathbb{1}_\Omega(x)f(x) = \begin{cases} f(x) & x \in \Omega \\ 0 & x \notin \Omega \end{cases}$. Then

$$u(x) = \int_{\Omega} G(x-y)f(y) dy = \int_{\mathbb{R}^d} G(x-y)\tilde{f}(y) dy = (G \star \tilde{f})(x)$$

We have $u \in L^1_{loc}(\mathbb{R}^d)$, so $u \in L^1(\Omega)$. Then $-\Delta u = \tilde{f}$ in $D'(\mathbb{R}^d)$, so $-\Delta u = f$ in $D'(\Omega)$. Claim: $-\Delta u = f$ in $D'(\mathbb{R}^d)$, so $-\Delta u = f$ in $D'(\Omega)$ if $\Omega \subseteq \mathbb{R}^d$, $\tilde{f}|_\Omega = f$. Take $\phi \in C_c^\infty(\Omega)$. We need: $(-\Delta u)(\phi) \stackrel{?}{=} \int_{\Omega} f\phi$. We have $\phi \in C_c^\infty(\Omega)$, so $\phi C_c^\infty(\mathbb{R}^d)$. This implies:

$$(-\Delta u)(\phi) = \int_{\mathbb{R}^d} \tilde{f}\phi = \int_{\substack{\Omega, \\ \text{supp } \phi \subseteq \Omega}} \tilde{f}\phi = \int_{\Omega} f\phi \quad \blacksquare$$

Exercise 4.21 (E 5.5) Let $B = B(0, \frac{1}{2}) \subseteq \mathbb{R}^3$. Consider $u : B \rightarrow \mathbb{R}$, defined by

$$u(x) = \log |\log |x||.$$

Prove that the distributional derivative $f = -\Delta u$ is a function in $L^{\frac{3}{2}}(B)$.

Solution.

$$\begin{aligned} \omega(r) &= \log(-\log(r)), \quad \text{for } r \in \left(0, \frac{1}{2}\right) \\ \omega'(r) &= \frac{1}{-\log(r)} \left(-\frac{1}{r}\right) = \frac{1}{r \log r} \\ \omega''(r) &= -\frac{1}{(r \log(r))^2} (r \log(r))' = -\frac{\log(r) + 1}{(r \log r)^2} \end{aligned}$$

So we have

$$-\Delta u = \omega''(r) = \frac{1}{(r \log r)^2} - \frac{1}{r^2 \log(r)} = f(r)$$

We show that $f \in L^{\frac{3}{2}}$:

$$\begin{aligned} \int_B |f(x)|^{\frac{3}{2}} dx &= \text{const} \int_0^{\frac{1}{2}} \left| \frac{1}{r^2(\log r)^2} - \frac{1}{r^2 \log r} \right|^{\frac{3}{2}} r^2 dr \\ &\lesssim \int_0^{\frac{1}{2}} \frac{1}{r} \left| \frac{1}{(\log(r))^2} - \frac{1}{(\log(r))} \right|^{\frac{3}{2}} dr \\ \left(\begin{array}{l} r = e^{-x}, \\ x \in (\log(2), \infty), \\ dr = -e^{-x} dx \end{array} \right) &\lesssim \int_{\log(2)}^{\infty} e^x \left(\frac{1}{x^2} + \frac{1}{x} \right)^{\frac{3}{2}} e^{-x} dx \\ &\lesssim \int_{\log(2)}^{\infty} \frac{1}{x^{\frac{3}{2}}} dx < \infty \end{aligned}$$

Where \lesssim means *up to a constant*. Now, $u(x) = \omega(r) = \log(-\log(r))$.

$$-\Delta u(x) = f(r) = \frac{1}{r^2(\log(r))^2} - \frac{1}{r^2 \log(r)}$$

for all $x \neq 0, |x| = r < \frac{1}{2}$. Why is $-\Delta u(x) = f$ in $D'(B)$? Take $\phi \in C_c^\infty(B)$, check: $\int_B u(-\Delta\phi) = \int_B f\phi$.

$$\int_{|x| < \frac{1}{2}} u(-\Delta\phi) dx = \lim_{\epsilon \rightarrow 0^+} \int_{\epsilon < |x| < \frac{1}{2}} u(x)(-\Delta\phi)(x) dx$$

by Dominated convergence. $u \in L^1(B)$. For all $\epsilon > 0$:

$$\begin{aligned} \int_{\epsilon < |x| < \frac{1}{2}} u(x)(-\Delta\phi)(x) dx &= \int_{|x| > \epsilon} u(x)(-\Delta\phi)(x) dx \\ &= \int_{\partial B(0, \epsilon)} u(x) \nabla \phi(x) \frac{x}{|x|} dS(x) + \int_{|x| > \epsilon} \nabla u(x) \nabla \phi(x) dx \end{aligned}$$

The boundary term vanishes as $\epsilon \rightarrow 0$ since

$$\left| u(x) \nabla \phi(x) \frac{x}{|x|} \right| \leq \|\nabla \phi\|_{L^\infty} |u(x)| = C \log |\log(r)|$$

$$\begin{aligned} \left| \int_{\partial B(0, \epsilon)} u(x) \nabla \phi(x) \frac{x}{|x|} dS(x) \right| &\leq C \int_{\partial B(0, \epsilon)} \log |\log(\epsilon)| dS(x) \\ &= C \log |\log \epsilon| \underbrace{|\partial B(0, \epsilon)|}_{\sim \epsilon^2} \xrightarrow{\epsilon \rightarrow 0} 0 \end{aligned}$$

$$\begin{aligned} \int_{|x| > \epsilon} \nabla u(x) \nabla \phi(x) dx &= \sum_{i=1}^d \int_{|x| > \epsilon} \partial_i u(x) \partial_i \phi(x) dx \\ &= \sum_{i=1}^d \left(- \int_{\partial B(0, \epsilon)} \partial_i u(x) \phi(x) \frac{x_i}{|x|} dS(x) - \int_{|x| > \epsilon} \underbrace{\partial_i \partial_i u(x)}_{f(x)} \phi(x) dx \right) \end{aligned}$$

The boundary term vanishes as $\epsilon \rightarrow 0$ as

$$\begin{aligned} \left| \int_{\partial B(0, \epsilon)} \partial_i u(x) \phi(x) \frac{x_i}{|x|} dS(x) \right| &\leq \|\phi\|_{L^\infty} \int_{\partial B(0, \epsilon)} |\partial_i u(x)| dS(x) \\ (\star) \quad &\leq C \frac{1}{|\epsilon \log(r)|} |\partial B(0, \epsilon)| \rightarrow 0 \end{aligned}$$

as $\epsilon \rightarrow 0$. $(\star)u = u(r), u(x) = \omega(|x|), \partial_i u(x) = \omega(|x|) \frac{x_i}{|x|}, |\partial_i u(x)| \leq |\omega(|x|)| = \left| \frac{1}{r \log(r)} \right|$. Finally:

$$\int_{|x| > \epsilon} f(x) \phi(x) dx \xrightarrow{\epsilon \rightarrow 0} \int_{\mathbb{R}^d} f(x) \phi(x) dx$$

Since $f\phi \in L^1$ and Dominated Convergence. ■

Exercise 4.22 (Bonus 5) Construct $u \in L^1(\mathbb{R}^3)$ compactly supported s.t. $-\Delta u \in L^{\frac{3}{2}}(\mathbb{R}^3)$ and u is not continuous at 0.

Hint: Related to E 5.5. $u_0(x) = \omega(r) = \log(|\log(r)|)$ if $0 < r = |x| < \frac{1}{2}$. Consider χu_0 where $\chi \in C_c^\infty$, $\chi = 0$ if $|x| > \frac{1}{2}$, $\chi = 1$ if $|x| < \frac{1}{4}$. You can prove that $\Delta(\chi u_0) = (\Delta\chi)u_0 + 2\nabla\chi\nabla u_0 + \chi(\underbrace{\Delta u_0}_{\in L^{\frac{3}{2}}})$ in $D'(\mathbb{R}^3)$. (almost everywhere, in distributional sense, integration by parts)

Theorem 4.23 (Regularity on Domains) Let $\Omega \subseteq \mathbb{R}^d$ be open. Assume $u, f \in D'(\Omega)$ such that $-\Delta u = f$ in $D'(\Omega)$.

- a) If $f \in L_{loc}^1(\Omega)$, then
 - $u \in C^1(\Omega)$ if $d = 1$
 - $u \in L_{loc}^q(\Omega)$ for all $q < \infty$ if $d = 2$
 - $u \in L_{loc}^q(\Omega)$ for all $q < \frac{d}{d-2}$ if $d \geq 3$
- b) If $f \in L_{loc}^q(\Omega)$, $d \geq p < \frac{d}{2}$, then $u \in C_{loc}^{0,\alpha}(\Omega)$, where $0 < \alpha < 2 - \frac{d}{p}$
- c) If $f \in L_{loc}^p(\Omega)$, $p > df$, then $u \in C_{loc}^{1,\alpha}(\Omega)$, where $0 \leq \alpha < 1 - \frac{d}{p}$
- d) If $f \in C_{loc}^{0,\alpha}(\Omega)$ for some $0 < \alpha < 1$, then $u \in C_{loc}^{2,\alpha}(\Omega)$
- e) If $f \in C_{loc}^{m,\alpha}(\Omega)$, then $u \in C_{loc}^{m+2,\alpha}(\Omega)$

Proof. Let $\mathbb{K} \in \{\mathbb{R}, \mathbb{C}\}$. Take a ball $\bar{B} \subseteq \Omega$. Define $f_B : \mathbb{R}^d \rightarrow \mathbb{K}$,

$$f_B(x) = (\mathbb{1}_B f)(x) = \begin{cases} f(x) & x \in B \\ 0 & x \notin B \end{cases}$$

Then if $f \in L_{loc}^1(\Omega)$, f_B is compactly supported. From the previous theorems: $G \star f_B \in L_{loc}^1(\mathbb{R}^d)$ and $-\Delta(G \star f_B) = f_B$ in $D'(\mathbb{R}^d)$. On the other hand, $-\Delta u = f$ in $D'(\Omega)$, so $-\Delta(u - G \star f_B) = 0$ in $D'(B)$. Indeed, for all $\phi \in C_c^\infty(B)$, then:

$$(-\Delta u)(\phi) = \int_{\Omega} f\phi = \int_B f_B\phi = - \int_{\mathbb{R}^d} f_B\phi = (-\Delta)(G \star f_B)(\phi)$$

Then $-\Delta u = -\Delta(G \star f_B)$ in $D'(B)$. Then $u - G \star f_B$ is harmonic in B and by Weyl's lemma we have $u - G \star f_B \in C^\infty(B)$. So the smoothness of u in B is the same to that of $G \star f$. ■

Exercise 4.24 (E 6.1) Show that If $\chi \in C^\infty(\mathbb{R}^d)$, then $f \in W^{1,p}(\mathbb{R}^d)$, $1 \leq p < \infty$, then $\chi f \in W_{loc}^{1,p}(\mathbb{R}^d)$ and

$$\partial_i(\chi f) = (\partial_i \chi)f + \chi(\partial_i f) \quad \text{in } D'(\mathbb{R}^d)$$

Solution. $\chi f \in L_{loc}^p(\mathbb{R}^d)$ obvious. $\partial(\chi f) \in L_{loc}^p(\mathbb{R}^d)$ is nontrivial but follows from $\partial_i(\chi f) = \underbrace{(\partial_i \chi)f + \chi(\partial_i f)}_{\in L_{loc}^p}$ in $D'(\mathbb{R}^d)$. To compute the distributional derivative

$\partial_i(\chi f)$, then: Take $\phi \in C_c^\infty(\mathbb{R}^d)$:

$$- \int_{\mathbb{R}^d} \chi f(\partial_i \phi) = \int_{\mathbb{R}^d} (?)\phi$$

We have

$$\begin{aligned}
-\int_{\mathbb{R}^d} \chi f(\partial_i \phi) &= -\int_{\mathbb{R}^d} f(\chi \partial_i \phi) \\
(\chi \partial_i \phi = (\partial_i \chi) \phi + \chi(\partial_i \phi)) &= -\int_{\mathbb{R}^d} f(\partial_i(\chi \phi) - (\partial_i \chi) \phi) \\
&= -\int_{\mathbb{R}^d} f \underbrace{\partial_i(\chi \phi)}_{\in C_c^\infty} + \int_{\mathbb{R}^d} f(\partial_i \chi) \phi \\
&= \int_{\mathbb{R}^d} (\partial_i f) \chi \phi + \int_{\mathbb{R}^d} f(\partial_i \chi) \phi \\
&= \int_{\mathbb{R}^d} ((\partial_i f) \chi + f(\partial_i \chi)) \phi
\end{aligned}$$

So $\partial_i(\chi f) = (\partial_i f) \chi + f(\partial_i \chi)$ in $D'(\mathbb{R}^d)$. ■

Remark 4.25 Question: If $\chi \in C^1(\mathbb{R}^d)$, $f \in W^{1,p}(\mathbb{R}^d)$. Is this it still correct that $\partial_i(\chi f) = (\partial_i \chi) f + \chi(\partial_i f)$ in $D'(\mathbb{R}^d)$?

Proof. It suffices to show that we still can apply intergration by parts.

$$(\star) \quad -\int f \partial_i g \stackrel{?}{=} \int (\partial_i f) g$$

Approximation: (\star) is correct if $g \in C_c^\infty$

- If $g \in C_c^1$, there is $\{g_n\} \subseteq C_c^\infty$ s.t. $g_n \rightarrow g$ in $W_{loc}^{1,p}$, $\frac{1}{p} + \frac{1}{q} = 1$.

$$\int (\partial_i g) f \xrightarrow{n \rightarrow \infty} - \int \underbrace{f}_{L^p} \underbrace{\partial_i g_n}_{\rightarrow \partial_i g \text{ in } L^q} = \int \underbrace{(\partial_i f)}_{\in L^p} \underbrace{g_n}_{\rightarrow g \text{ in } L^q} \xrightarrow{n \rightarrow \infty} \int (\partial_i f) g$$

■

Exercise 4.26 (E 6.2) \mathbb{R}^2 , $G(x) = -\frac{1}{2\pi} \log |x|$. Let $f \in L^p(\mathbb{R}^d)$, compactly supported. Define $u(x) = (G \star f)(x) = \int_{\mathbb{R}^2} G(x-y) f(y) dy$

1. If $p = 1$, then $u \in L_{loc}^q(\mathbb{R}^2)$ for all $q < \infty$.
2. If $p > 2$, then $u \in C^{1,\alpha}$ with $0 < \alpha < 1 - \frac{2}{p}$.

Solution. 1. Take any ball $B = B(0, R)$ and:

$$\begin{aligned}
\int_B |u(x)|^q dx &= \int_B \left(\int_{\mathbb{R}^d} |G(x-y)| |f(y)| dy \right)^q dx \\
&\leq C \int_B \left(\int_{\mathbb{R}^2} |G(x-y)|^q |f(y)| dy \right) dx \\
&= C \int_{\mathbb{R}^2} \left(\int_B |G(x-y)|^q dx \right) |f(y)| dy
\end{aligned}$$

Recall from the proof of Youngs inequality:

$$\begin{aligned}
|u(x)| &= \left| \int_{\mathbb{R}^2} G(x-y) f(y) dy \right| \\
&\leq \int_{\mathbb{R}^2} |G(x-y)| |f(y)| dy \\
&\leq \left(\int_{\mathbb{R}^2} |G(x-y)|^q |f(y)| dy \right)^{\frac{1}{q}} \left(\int_{\mathbb{R}^2} |f(y)| dy \right)^{\frac{1}{q'}}, \quad \frac{1}{q} + \frac{1}{q'} = 1
\end{aligned}$$

Assume $\text{supp } f \subseteq \overline{B(0, R)}$. Then if $y \in \text{supp } f$ and $x \in B(0, R)$, then $|x-y| \leq |x| + |y| \leq R + R_1$. For all $y \in \text{supp } f$:

$$\begin{aligned}
\int_{B(0, R)} |G(x-y)|^q dx &\leq \int_{|x-y| \leq R+R_1} |G(x-y)|^q dx \\
&= \int_{|z| \leq R+R_1} |G(z)|^q dz < \infty
\end{aligned}$$

as $G \in L_{loc}^q$ ($|G(z)| = \frac{1}{2\pi} |\log(z)| \leq \frac{C_{R+R_1, \epsilon}}{|z|^\epsilon}$ for all $|z| \leq R + R_1$), so

$$\int_{|z| \leq R+R_1} |G(z)|^q \leq C_{R+R_1, \epsilon} \int_{|z| \leq R+R_1} \frac{1}{|z|^{\epsilon q}} dz < \infty$$

if $\epsilon q < 2$.

2. Recall $\partial_i u \in L_{loc}^1(\mathbb{R}^2)$ and:

$$\partial_i u(x) = (\partial_i G \star f)(x) = c \int_{\mathbb{R}^2} \frac{x_i - y_i}{|x - y|^2} f(y) dy$$

First we show $\partial_i u \in C^{0, \alpha}$:

$$\begin{aligned}
|\partial_i u(x) - \partial_i u(z)| &= \left| C \int_{\mathbb{R}^2} \left(\frac{x_i - y_i}{|x - y|^2} - \frac{z_i - y_i}{|z - y|^2} \right) f(y) dy \right| \\
&\leq C \int_{\mathbb{R}^2} \left| \frac{x_i y_i}{|x - y|^2} - \frac{z_i y_i}{|z - y|^2} \right| |f(y)| dy \\
&\stackrel{?}{\leq} C |x - z|^\alpha
\end{aligned}$$

Note that

$$\begin{aligned}
\left| \frac{x_i - y_i}{|x - y|^2} - \frac{z_i - y_i}{|z - y|^2} \right| &= \left| (x_i - y_i) \left(\frac{1}{|x - y|^2} - \frac{1}{|z - y|^2} \right) + \frac{x_i - z_i}{|z - y|^2} \right| \\
&\leq |x_i - y_i| \left| \frac{1}{|x - y|^2} - \frac{1}{|z - y|^2} \right| + \frac{|x_i - z_i|}{|z - y|^2} \\
&\leq C |z - x|^\alpha \left(\frac{1}{|x - y|^{1+\alpha}} + \frac{1}{|z - y|^{1+\alpha}} + \frac{|x - z|}{|z - y|^2} \right)
\end{aligned}$$

Here $|x_i - z_i| \leq |x - z|$ and $|x_i - y_i| \leq |x - y|$ and:

$$\begin{aligned}
\underbrace{\left| \frac{1}{|x - y|^2} - \frac{1}{|z - y|^2} \right|}_{\text{sym } x \leftrightarrow z} &= \left| \frac{1}{|x - y|^2} - \frac{1}{|z - y|^2} \right| = \left| \frac{1}{|x - y|} - \frac{1}{|z - y|} \right| \left| \frac{1}{|x - y|} + \frac{1}{|z - y|} \right| \\
&= \frac{||z - y| - |x - y||}{|x - y| |z - y|} \left| \frac{1}{|x - y|} + \frac{1}{|z - y|} \right| \\
&\leq |z - x|^\alpha \frac{\max(|z - y|, |x - y|)^{1-\alpha}}{|x - y| |z - y|} \left(\frac{1}{|x - y|} + \frac{1}{|z - y|} \right) \\
&\leq C |z - x|^\alpha \left(\frac{1}{|x - y|^{2+\alpha}} + \frac{1}{|z - y|^{2+\alpha}} \right)
\end{aligned}$$

By the symmetrie $x \leftrightarrow z$:

$$\begin{aligned}
LHS &\leq C|z-x|^\alpha \left(\frac{1}{|x-y|^{1+\alpha}} + \frac{1}{|z-y|^{1+\alpha}} \right) + \frac{|x-y|}{|x-y|^2} \\
&\Rightarrow LHS \leq C \cdots + |x-z| \min \left(\frac{1}{|z-y|^2}, \frac{1}{|x-y|^2} \right) \\
&\leq (|x-y| + |z-y|)^{1-\alpha} \\
&C|z-x|^\alpha \left(\frac{1}{|x-y|^{1+\alpha}} + \frac{1}{|z-y|^{1+\alpha}} \right)
\end{aligned}$$

In summary:

$$\begin{aligned}
|\partial_i u(x) - \partial_i u(z)| &\leq C \int_{\mathbb{R}^2} \left| \frac{x_i - y_i}{|x-y|^2} - \frac{z_i - y_i}{|z-y|^2} \right| |f(y)| dy \\
&= C|x-y|^\alpha \int_{\mathbb{R}^2} \left(\frac{1}{|x-y|^{1+\alpha}} + \frac{1}{|z-y|^{1+\alpha}} \right) |f(y)| dy
\end{aligned}$$

Consider if $|x| > 2R_1$:

$$\int_{\mathbb{R}^2} \frac{1}{|x-y|^{1+\alpha}} |f(y)| dy \leq \int_{\mathbb{R}^2} \frac{1}{R_1^{1+\alpha}} |f(y)| dy \leq C$$

$\text{supp } f \subseteq B(0, R_1)$. If $|x| < 2R_1$, then $|x-y| \leq 3R$ if $y \in B(0, R_1)$. Hence:

$$\begin{aligned}
&\int_{|x-y| \leq 3R_1} \frac{1}{|x-y|^{1+\alpha}} |f(y)| dy \\
&\leq \left(\int_{|x-y| \leq 3R_1} \frac{1}{|x-y|^{(1+\alpha)p'}} \right)^{\frac{1}{p'}} \left(\int |f(y)|^p dy \right)^{\frac{1}{p}} \\
&= \int_{|z| \leq 3R_1} \frac{1}{|z|^{(1+\alpha)p'}} dz < \infty
\end{aligned}$$

So $\alpha < 1 - \frac{2}{p}$. ■

Exercise 4.27 (E 6.3) Let $f \in C_{loc}^{0,\alpha}$ and $-\Delta u = f$ in $D'(\Omega)$. Prove $u \in C_{loc}^{2,\alpha}(\Omega)$.

Solution. Take an open ball $B \subseteq \bar{B} \subseteq \Omega$. We prove $u \in C^{2,\alpha}(B)$. There is an open Ω_B s.t. $\bar{B} \subseteq \bar{\Omega}_B \subseteq \Omega$. Then there is a $\chi_B \in C_c^\infty(\mathbb{R}^d)$ s.t. $\chi_B(x) = 1$ if $x \in B$ and $\chi_B(x) = 0$ if $x \notin \Omega_B$. Define

$$f_B(x) = \chi_B(x)f(x) : \mathbb{R}^d \rightarrow \mathbb{R}$$

We prove that $f_B \in C^{0,\alpha}(\mathbb{R}^d)$. Since $f \in C_{loc}^{0,\alpha}(\Omega)$ we have $f \in C^{0,\alpha}(\Omega)$, so $|f(x) - f(y)| \leq C|x-y|^\alpha$ for all $x, y \in \Omega_B$. Then:

$$\begin{aligned}
|f_B(x) - f_B(y)| &= |\chi_B(x)f(x) - \chi_B(y)f(y)| \\
&\leq |(\chi_B(x) - \chi_B(y))f(x) + \chi_B(y)(f(x) - f(y))| \\
&\leq C|x-y|^\alpha \|f\|_{L^\infty} + C\|\chi\|_{L^\infty(\Omega_B)} |x-y|^\alpha \leq C_{\Omega_B} |x-y|^\alpha
\end{aligned}$$

What about other cases? If x, y are bot not in Ω_B , then $|f_B(x) - f_B(y)| = 0$, then if $x \in \Omega_B$ and $y \notin \Omega_B$: $|f_B(x) - f_B(y)| = |f_B(x)| = |\chi_B(x)||f(x)| = |\chi_B(x) - \chi_B(y)||f(x)| \leq C|x-y|^\alpha$. Conclusion: $|f_B(x) - f_B(y)| \leq C|x-y|^\alpha$ for all $x, y \in \mathbb{R}^d$, i.e. $f_B \in C^{0,\alpha}(\mathbb{R}^d)$. Also f_B is compactly supported. By a theorem in the lecture: $G \star f_B \in C^{2,\alpha}(\mathbb{R}^d)$. Finally: $-\Delta u = f$ in $D'(\Omega)$, $-\Delta(G \star f_B) = f_B$ in $D'(\mathbb{R}^d)$. So we conclude $-\Delta u = f = f_B = -\Delta(G \star f_B)$ in $D'(B)$. $-\Delta(u - G \star f_B) = 0$ in $D'(B)$, so $u - G \star f_B \in C^\infty(B)$, so $u \in C^{2,\alpha}(B)$. ■

Exercise 4.28 (E 6.4) $u, f \in L^2(\mathbb{R}^d)$, $-\Delta u = f$ in $D'(\mathbb{R}^d)$. Prove $u \in W^{2,2}(\mathbb{R}^d)$, $\|u\|_{W^{2,2}(\mathbb{R}^d)} \leq C(\|u\|_{L^2} + \|f\|_{L^2})$.

$$\begin{aligned} W^{2,2}(\mathbb{R}^d) &= \{g \in L^2(\mathbb{R}^d) \mid D^\alpha g \in L^2 \text{ for all } |\alpha| \leq 2\} \\ &= \{g \in L^2(\mathbb{R}^d) \mid \widehat{D^\alpha g}(k) = (-2\pi i k)^\alpha \hat{g}(k) \in L^2(\mathbb{R}^d) \text{ for all } |\alpha| \leq 2\} \\ &= \{g \in L^2(\mathbb{R}^d) \mid (1 + |k|^2)\hat{g}(k) \in L^2(\mathbb{R}^d)\} \end{aligned}$$

$\|u\|_{W^{2,2}(\mathbb{R}^d)}$ is comparable $\int_{\mathbb{R}^d} (1 + |k|^2)^2 |\hat{g}(k)|^2 dk$. If $D^\alpha g \in L^2$, then $\widehat{D^\alpha g}(k) = (-2\pi i k)^\alpha \hat{g}(k)$. For any $\phi \in C_c^\infty(\mathbb{R}^d)$:

$$\begin{aligned} \int \widehat{D^\alpha g}(k) \hat{\phi}(k) dk &= \int (D^\alpha g) \phi = (-1)^{|\alpha|} \int g (D^\alpha \phi) \\ &= (-1)^{|\alpha|} \int \tilde{g}(k) \widehat{D^\alpha \phi}(k) \\ &= (-1)^{|\alpha|} \int \tilde{g}(k) (-2\pi i k)^\alpha \hat{\phi}(k) dk \end{aligned}$$

so $\hat{D^\alpha g}(k) = (-1)^{|\alpha|} \hat{g}(k) \overline{(-2\pi i k)^\alpha} = \hat{g}(k) (-2\pi i k)^\alpha$. This implies:

$$\begin{aligned} \|u\|_{W^{2,2}(\mathbb{R}^d)} &\leq C \int_{\mathbb{R}^d} (1 + |k|^2)^2 |\hat{u}(k)|^2 dk \\ &= C \left(\|u\|_{L^2}^2 + \int_{\mathbb{R}^d} |k|^4 |\hat{u}(k)|^2 dk \right) \\ &\leq C (\|u\|_{L^2}^2 + \|f\|_{L^2}^2) \\ &\leq C (\|u\|_{L^2} + \|f\|_{L^2})^2 \end{aligned}$$

Remark 4.29 (Bonus 6) Let $f, g \in W^{1,2}(\mathbb{R}^d)$. Prove that $fg \in W^{1,1}(\mathbb{R}^d)$ and

$$\partial_i(fg) = (\partial_i f)g + f(\partial_i g) \quad \text{in } D'(\mathbb{R}^d)$$

Chapter 5

Existence for Poisson's Equation on Domains

Let $\Omega \subseteq \mathbb{R}^d$ be open. Consider Poisson's equation.

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = g & \text{on } \partial\Omega \end{cases}$$

for given data (f, g) and u the unknown function.

- Classical solutions: $f \in C^2(\bar{\Omega}) \rightsquigarrow$ explicit representation formula.
- Weak solution: $f \in L^p(\Omega)$, $g \in L^p(\partial\Omega) \rightsquigarrow u \in W^{2,p}(\Omega)$. We are going to establish the existence by *Energy Methods*. (Calculus of variations)

Definition 5.1 (C^1 -Domains) Let $\Omega \subseteq \mathbb{R}^d$ be open. We say that Ω is of class C^1 (i.e. $\partial\Omega \in C^1$) if for all $x_0 \in \partial\Omega$ there is a bijective function $h : U \rightarrow Q$, where

- $x_0 \in U$ open in \mathbb{R}^d
- $Q = \{x = (x_1, \dots, x_d) = (x', x_d)\} \in \mathbb{R}^{d-1} \times \mathbb{R} \mid |x'| < 1, |x_d| < 1\}$
- $h \in C^1(\bar{U})$ and $h^{-1} \in C^1(\bar{Q})$ (C^1 -diffeomorphism)
- $h(U) = Q$

$$\begin{aligned} h(U \cap \Omega) &= Q_+ = Q \cap \mathbb{R}_+^d = \{x = (x', x_d) \in Q \mid x_d > 0\} \\ h(U \cap \partial\Omega) &= Q_0 = Q \cap \partial\mathbb{R}_+^d = \{x = (x', x_d) \in Q \mid x_d = 0\} \\ h(U \setminus \bar{\Omega}) &= Q_- = Q \cap \mathbb{R}_-^d = \{x = (x', x_d) \in Q \mid x_d < 0\} \end{aligned}$$

(From Brezis' book)

Remark 5.2 The set Q can be replaced by a ball, i.e. Ω is of C^1 if for all $x_0 \in \partial\Omega$ there is a function $U \rightarrow B(0, 1) \subseteq \mathbb{R}^d$.

- $x_0 \in U$ with $U \subseteq \mathbb{R}^d$ open.
- $h \in C^1(\bar{U})$, $h^{-1} \in C^1(\overline{B(0, 1)})$
- $h(U \cap \Omega) = B(0, 1) \cap \mathbb{R}_+^d$, $h(U \cap \partial\Omega) = B(0, 1) \cap \mathbb{R}^d$.

Remark 5.3 (An equivalent definition from Evan's book App. C) Let $\Omega \subseteq \mathbb{R}^d$ be open. Then Ω is C^1 if for all $x_0 \in \partial\Omega$ there is a $r > 0$ and a C^1 -function $\gamma : \mathbb{R}^{d-1} \rightarrow \mathbb{R}$ s.t. (upon relabeling and reorienting the axes if necessary) such that:

$$\Omega \cap B(x_0, r) = \{x = (x', x_d) \in B(x_0, r) \mid x_d < \gamma(x')\}$$

Proof of the equivalence of the two definitions.

Def. 2 \Rightarrow Def. 1: In fact, given $x_0 \in \partial\Omega$ and γ we can define

$$\begin{aligned} h(x', x_d) &= (x', x_d - \gamma(x')) \in C^1(\mathbb{R}^d, \mathbb{R}^d) \\ h^{-1}(x', x_d) &= (x', x_d + \gamma(x')) \in C^1(\mathbb{R}^d, \mathbb{R}^d) \end{aligned}$$

Def. 1 \Rightarrow Def. 2: We need the inverse function theorem and the implicit function theorem. Let $x_0 \in \partial\Omega$, let $h : U \rightarrow B(0, 1)$ as in Def. 1. Denote $h = (h_1, h_2, \dots, h_d)$. Since h is invertible near x_0 , by the inverse function theorem we have for the Jacobi matrix $Jh(x_0) = (\partial_j h_i(x_0))_{1 \leq i, j \leq d}$ is invertible. So we have $\nabla h_d(x_0) = (\partial_j h_d(x_0))_{1 \leq j \leq d} \neq \vec{0}^{\mathbb{R}^d}$, so there is a $j \in \{1, 2, \dots, d\}$ s.t. $\partial_j h_d(x_0) \neq 0$. By relabeling and reorienting the axes, we can assume that $\partial_d h_d(x_0) > 0$. By continuity there is a $r > 0$ such that $\partial_d h_d(x) > 0$ for all $x \in B(x_0, r)$. Define $\gamma : \mathbb{R}^{d-1} \rightarrow \mathbb{R}$ s.t. in $B(x_0, r)$:

$$x = (x', x_d) \in \partial\Omega \iff h_d(x', x_d) = 0 \iff x_d = \gamma(x'),$$

$h_d : \mathbb{R}^d \rightarrow \mathbb{R}$. This gives a solution γ if $\partial_d h_d > 0$ in $B(x_0, r)$. (For implicit function theorem, $\partial_d h_d(x_0) \neq 0$) Question: Why in $B(x_0, r)$?

$$x = (x', x_d) \in \Omega \iff x_d > \gamma(x')$$

Since $\partial_d h_d(x) > 0$ for all $x \in B(x_0, r)$ we have that $x_d \mapsto h_d(x', x_d)$ is strictly increasing, hence

$$\begin{aligned} x &= (x', x_d) \in \Omega \\ \iff h(x', x_d) &\in \mathbb{R}_+^d \\ \iff h_d(x', x_d) &> 0 = h_d(x', \gamma(x')) \\ \iff x_d &> \gamma(x') \end{aligned} \quad \blacksquare$$

Theorem 5.4 (Gauss-Green formula / Integration by parts) Let $\Omega \subseteq \mathbb{R}^d$ be open and bounded. Then

1. For all $u, v \in C^1(\bar{\Omega})$:

$$\int_{\Omega} (\partial_i u) v = - \int_{\Omega} u (\partial_i v) + \int_{\partial\Omega} u v n_i dS,$$

where $\vec{n} = (n_i)_{i=1}^d$ is the outwards unit normal vector.

2. For all $u, v \in C^2(\bar{\Omega})$:

$$\int_{\Omega} u (-\Delta v) = \int_{\Omega} \nabla u \nabla v - \int_{\partial\Omega} u \frac{\partial v}{\partial \vec{n}} dS$$

where $\frac{\partial v}{\partial \vec{n}} = \nabla v \vec{n} = \sum_{i=1}^d \partial_i v n_i$.

Classical solutions via Green's function:

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = g & \text{on } \partial\Omega \end{cases}$$

Let $\Omega \subseteq \mathbb{R}^d$ be open, bounded, $\partial\Omega \in C^1$. Assume there exists a $u \in C^2(\bar{\Omega})$, $f \in C(\bar{\Omega})$, $g \in C(\partial\Omega)$. Let G be the fundamental solution of the Laplace Equation in \mathbb{R}^d . We use integration by parts in $\Omega \setminus B(x, \epsilon)$:

$$\begin{aligned} & \int_{\Omega \setminus B(x, \epsilon)} u(y)(-\Delta G)(y-x) dy \\ &= \int_{\Omega \setminus B(x, \epsilon)} \nabla u(y) \nabla G(y-x) dy - \int_{\partial\Omega \cup \partial B(x, \epsilon)} u(y) \frac{\partial G}{\partial \vec{n}}(y-x) dS(y) \\ & \int_{\Omega \setminus B(x, \epsilon)} G(y-x)(-\Delta u)(y) dy \\ &= \int_{\Omega \setminus B(x, \epsilon)} \nabla G(y-x) \nabla u(y) dy - \int_{\partial\Omega \cup \partial B(x, \epsilon)} G(y-x) \frac{\partial u}{\partial \vec{n}}(y) dS(y) \end{aligned}$$

This implies:

$$\begin{aligned} & \int_{\Omega \setminus B(x, \epsilon)} [u(y)(-\Delta G(y-x)) - G(y-x)(-\Delta u)(y)] dy \\ &= - \int_{\partial\Omega \cup \partial B(x, \epsilon)} \left[u(y) \frac{\partial G}{\partial \vec{n}}(y-x) - G(y-x) \frac{\partial u}{\partial \vec{n}}(y) \right] dS(y) \end{aligned}$$

for all $x \in \Omega$, $x \in B(x, \epsilon) \subseteq \Omega$. When $\epsilon \rightarrow 0$, then the left hand side converges to $-\int_{\Omega} G(y-x)f(y) dy$ and the right hand side (for $d \geq 2$) we have $\partial_j G(y) = \frac{-y_j}{d|B_1||y|^d}$, so

$$\frac{\partial G}{\partial \vec{n}} = \nabla G \vec{n} = \nabla G(y) \left(\frac{-y}{|y|} \right) = \sum_{j=1}^d \frac{-y_i}{d|B_1||y|^d} \frac{-y_j}{|y|} = \frac{1}{d|B_1||y|^{d-1}} \text{ on } \partial B(0, \epsilon)$$

so we have

$$\frac{\partial G}{\partial \vec{n}}(y-x) = \frac{1}{d|B_1|\epsilon^{d-1}}$$

on $\partial B(x, \epsilon)$. Hence

$$\begin{aligned} \int_{\partial B(x, \epsilon)} u(y) \frac{\partial G}{\partial \vec{n}}(y-x) dS(y) &= \frac{1}{d|B_1|\epsilon^{d-1}} \int_{\partial B(x, \epsilon)} u(y) dS(y) \\ &= \oint_{\partial B(x, \epsilon)} u(y) dS(y) \xrightarrow{\epsilon \rightarrow 0} u(x) \end{aligned}$$

On the other hand:

$$\left| \int_{\partial B(x, \epsilon)} G(y-x) \frac{\partial u(y)}{\partial \vec{n}} dS(y) \right| \leq C\epsilon^{d-1} \sup_{|z|=\epsilon} |G(z)| \xrightarrow{\epsilon \rightarrow 0} 0$$

since $|G(z)| \leq \frac{C}{|z|^{\frac{d-2}{2}}}$ if $d \geq 3$, $|G(z)| \leq C|\log(z)|$ if $d = 2$ and $|G(z)| \leq C|z|$ if $d = 1$.

In summary:

$$\begin{aligned} & - \int_{\Omega} G(y-x)f(y) dy = - \int_{\partial\Omega} \left[u(y) \frac{\partial G}{\partial \vec{n}}(y-x) - G(y-x) \frac{\partial u}{\partial \vec{n}}(y) \right] dS(y) - u(x) \\ & \Leftrightarrow u(x) = \int_{\Omega} G(y-x)f(y) dy + \int_{\partial\Omega} \left[G(y-x) \frac{\partial u}{\partial \vec{n}}(y) - g(y) \frac{\partial G}{\partial \vec{n}}(y-x) \right] dS(y) \end{aligned}$$

Problem: We don't know anything about $\frac{\partial u}{\partial \vec{n}}$ on $\partial\Omega$. Trick: We can resolve that by using the *corrector* function: $\Phi_x = \Phi_x(y)$ which solves:

$$\begin{cases} -\Delta \Phi_x = 0 & \text{in } \Omega \\ \Phi_x(y) = G(y-x) & \text{on } \partial\Omega \end{cases}$$

We assume that Φ_x exists.

Definition 5.5 (Green's function) $\tilde{G}(x-y) = G(y-x) - \Phi_x(y)$ for all $x, y \in \Omega$, $x \neq y$.

Exercise 5.6 (E 7.1) Let $\Omega \subseteq \mathbb{R}^d$ be open and bounded with C^1 boundary. For $x \in \Omega$, assume there exist $\Phi_x(y)$, $y \in \bar{\Omega}$, s.t.

$$\begin{cases} \Delta_y \Phi_x(y) = 0 \\ \Phi_x(y) = G(y-x) \end{cases},$$

$G(z) = \frac{1}{d(d-2)|B_1||z|^{d-2}}$, $d \geq 3$. Prove that $\Phi_x(y) = \Phi_y(x)$ for all $x, y \in \Omega$. Then $\tilde{G}(x, y) = G(y-x) - \Phi_x(y)$ is symmetric, i.e. $\tilde{G}(x, y) = \tilde{G}(y, x)$.

Solution. Assume $x \neq y$. Define

$$\begin{aligned} f(z) &= \tilde{G}(x, z) = G(z-x) - \Phi_x(z) \\ g(z) &= \tilde{G}(y, z) = G(z-y) - \Phi_y(z) \end{aligned}$$

Integration by parts:

$$\begin{aligned} \int_{\Omega \setminus (B(x, \epsilon) \cup B(y, \epsilon))} (f \Delta g - g \Delta f) &= \int_{\partial\Omega \cup \partial B(x, \epsilon) \cup \partial B(y, \epsilon)} \left(f \frac{\partial g}{\partial \vec{n}_z} - g \frac{\partial f}{\partial \vec{n}_z} \right) dS(z) \\ &= \int_{\partial B(x, \epsilon) \cup \partial B(y, \epsilon)} \left(f \frac{\partial g}{\partial \vec{n}_z} - g \frac{\partial f}{\partial \vec{n}_z} \right) dS(z) \end{aligned}$$

Consider $f \frac{\partial g}{\partial \vec{n}_z}$ on $\partial B(x, \epsilon)$. Since g is only singular at y , so $\left| \frac{\partial g}{\partial \vec{n}} \right| \leq C$ on $\partial B(x, \epsilon)$. This implies:

$$\begin{aligned} \int_{\partial B(x, \epsilon)} \left| f \frac{\partial g}{\partial \vec{n}_z} \right| dS(z) &\leq C \int_{\partial B(x, \epsilon)} |f| dS(z) \\ &\leq C \int_{\partial B(x, \epsilon)} \left(\frac{1}{|x-z|^{d-2}} + \|\Phi_x\|_{L^\infty(\Omega)} \right) dS(z) \\ &\leq C \epsilon^{d-1} \left(\frac{1}{\epsilon^{d-2}} + 1 \right) \leq C \epsilon \xrightarrow{\epsilon \rightarrow 0} 0 \end{aligned}$$

Consider $f \frac{\partial g}{\partial \vec{n}_z}$ on $\partial B(y, \epsilon)$. Decompose $\frac{\partial g}{\partial \vec{n}} = [\nabla_z G(z-y) - \nabla_z \Phi_y(z)] \frac{(z-y)}{|z-y|}$. Since $\Phi_y(z)$ is harmonic in Ω , we have that

$$\int_{\partial B(y, \epsilon)} \left| f \nabla_z \Phi_y(z) \frac{-(z-y)}{|z-y|} \right| \leq C \int_{\partial B(y, \epsilon)} |f| \leq C \epsilon^{d-1} \xrightarrow{\epsilon \rightarrow 0} 0$$

Thus the main contribution from $f \frac{\partial g}{\partial \vec{n}}$ is

$$\begin{aligned}
& \int_{\partial B(y, \epsilon)} f(z) \nabla_z G(z-y) \frac{-(z-y)}{|z-y|} dS(z) \\
&= \int_{\partial B(y, \epsilon)} f(z) \frac{-(z-y)}{d|B_1||z-y|^d} \frac{-(z-y)}{|z-y|} dS(z) \\
&= \frac{1}{d|B_1|\epsilon^{d-1}} \int_{\partial B(y, \epsilon)} f(z) dS(z) \\
&= \oint_{\partial B(y, \epsilon)} f(z) dS(z) = f(y)
\end{aligned}$$

In summary:

$$\int_{\partial B(x, \epsilon) \cup \partial B(y, \epsilon)} f \frac{\partial g}{\partial \vec{n}_z} dS(z) \xrightarrow{\epsilon \rightarrow 0} f(y)$$

Similary:

$$\int_{\partial B(x, \epsilon) \cup \partial B(y, \epsilon)} g \frac{\partial f}{\partial \vec{n}_z} dS(z) \xrightarrow{\epsilon \rightarrow 0} g(x)$$

So we have that $f(y) = g(x)$, so

$$\begin{aligned}
f(y) &= G(y-x) - \Phi_x(y) \\
g(x) &= G(x-y) - \Phi_y(x).
\end{aligned}$$

So $\Phi_x(y) = \Phi_y(x)$ for all $x \neq y \in \Omega$. This implies $\Phi_x(y) = \Phi_y(x)$ for all $x, y \in \Omega$. ■

Theorem 5.7 Let $\Omega \subseteq \mathbb{R}^d$ be open, bounded and C^1 . If $u \in C^2(\Omega)$ solves

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = g & \text{on } \partial\Omega \end{cases},$$

then

$$u(x) = - \int_{\partial\Omega} g(y) \frac{\partial \tilde{G}}{\partial \vec{n}_y}(x, y) dS(y) + \int_{\Omega} \tilde{G}(x, y) dy$$

Proof. We need to prove:

$$\int_{\Omega} \Phi_x(y) f(y) dy + \int_{\partial\Omega} \left(-g(y) \frac{\partial \Phi_x(y)}{\partial \vec{n}_y} + G(y-x) \frac{\partial u}{\partial \vec{n}}(y) \right) = 0$$

By integration by parts:

$$\begin{aligned}
\int_{\Omega} \Phi_x(y) f(y) dy &= \int_{\Omega} \Phi_x(y) (-\Delta u(y)) dy \\
&= \int_{\Omega} [\Phi_x(y) (-\Delta u(y)) + (\Delta \Phi_x(y)) u(y)] dy \\
(\Delta \Phi_x(y) = 0) &= \int_{\partial\Omega} \left(-\Phi_x(y) \frac{\partial u}{\partial \vec{n}} + \frac{\partial \Phi_x(y)}{\partial \vec{n}} \underbrace{u(y)}_{g(y)} \right) dS(y) \quad \blacksquare
\end{aligned}$$

How can we compute $\Phi_x(y)$? It is not easy for general domains. But let us prove on two cases:

- $\Omega = \mathbb{R}_+^d$ (half-space)
- $\Omega = B(0, r)$ (a ball)

5.1 Green's function on the upper half plane

We use the following notation:

$$\begin{aligned}\mathbb{R}_+^d &= \{x = (x_1, x_2, \dots, x_d) = (x', x_d) \in \mathbb{R}^{d-1} \times \mathbb{R} \mid x_d > 0\} \\ \partial\mathbb{R}_+^d &= \{x = (x', x_d) \mid x_d = 0\} = \mathbb{R}^{d-1} \times \{0\}\end{aligned}$$

For all $x \in \mathbb{R}^d$ we want to find the correction function $\Phi_x(y)$ with $y \in \overline{\mathbb{R}_+^d}$ s.t.

$$\begin{cases} +\Delta_y \Phi_x(y) = 0 & \text{in } \mathbb{R}_+^d \\ \Phi_x(y) = G(y - x) & \text{in } \partial\mathbb{R}_+^d \end{cases}$$

Definition 5.8 (Reflection for \mathbb{R}_+^d) For all $x = (x', x_d) \in \mathbb{R}^d$, $\tilde{x} = (x', -x_d) \in \mathbb{R}^d$, (if $x \in \mathbb{R}_+^d \Rightarrow \tilde{x} \in \mathbb{R}_-^d$)

Claim: $\Delta_y \Phi_x(y) = G(y - \tilde{x})$ is a corrector function.

- $\Delta_y \Phi_x(y) = \Delta_y G(y - \tilde{x}) = 0$ for all $y \in \mathbb{R}_+^d$ for all $x \in \mathbb{R}_+^d$ (as $\tilde{x} \in \mathbb{R}_-^d = \mathbb{R}^d \setminus \overline{\mathbb{R}_+^d}$)
- $\Phi_x(y) = G(y - \tilde{x}) = G(y - x)$ on $y \in \partial\mathbb{R}_+^d$. In fact, $y \in \partial\mathbb{R}_+^d$, so $y_d = 0$, so

$$G(y - \tilde{x}) = G_0(|y - \tilde{x}|) = G_0\left(\sqrt{\sum_{i=1}^{d-1} |x_i - y_i|^2 + |x_d|^2}\right) = G_0(|y - x|)$$

Consider $f = 0$ and

$$\begin{cases} -\Delta = 0 & \text{in } \mathbb{R}_+^d \\ u = g & \text{on } \partial\mathbb{R}_+^d \end{cases}$$

Then we expect

$$u(x) = - \int_{\partial\Omega} g(y) \frac{\partial \tilde{G}}{\partial \vec{n}_y}(x, y) dS(y)$$

We compute

$$\frac{\partial \tilde{G}}{\partial \vec{n}_y}(x - y) = \sum_{j=1}^d \frac{\partial \tilde{G}}{\partial y_j}(x, y) \vec{n}_j = - \frac{\partial \tilde{G}}{\partial y_d}(x, y) = \frac{\partial}{\partial y_d} (G(y - \tilde{x}) - G(y - x)) = \dots$$

because $\tilde{G}(x, y) = G(y - x) - \Phi_x(y) = G(y - x) - G(y - \tilde{x})$.

$$\begin{aligned} \dots &= \frac{1}{d|B_1|} \left[\frac{-(y_d - \tilde{x}_d)}{|y - \tilde{x}|^d} - \frac{-(y_d - x_d)}{|y - x|^d} \right] \\ (y \in \partial\mathbb{R}_+^d) &= \frac{1}{d|B_1|} \left[\frac{\tilde{x}_d}{|y - x|} - \frac{x_d}{|y - x|^d} \right] = \frac{-2x_d}{d|B_1||y - x|^d} \end{aligned}$$

We expect

$$u(x) = - \int_{\partial\mathbb{R}_+^d} g(y) \frac{\partial \tilde{G}}{\partial \vec{n}_y}(x, y) dS(y) = \int_{\partial\mathbb{R}_+^d} g(y) \frac{2x_d}{d|B_1||y - x|^d} dS(y)$$

Theorem 5.9 Assume $g \in C(\mathbb{R}^{d-1}) \cap L^\infty(\mathbb{R}^{d-1})$ Then

$$u(x) = \int_{\partial\mathbb{R}_+^d} g(y) K(x, y) dS(y)$$

and

$$K(x, y) = \frac{2x_d}{d|B_1||y-x|^d} \quad \text{for all } x \in \mathbb{R}_+^d.$$

satisfies that $u \in C^\infty(\mathbb{R}_+^d) \cap L^\infty(\mathbb{R}_+^d)$ and

$$\begin{cases} \Delta u = 0 & \text{in } \mathbb{R}_+^d \\ \lim_{\substack{x \rightarrow 0 \\ x \in \mathbb{R}_+^d}} u(x) = g(x_0) & \forall x_0 \in \partial \mathbb{R}_+^d \end{cases}$$

Proof. Claim: For all $y \in \partial \mathbb{R}_+^d$, $x \mapsto K(x, y)$ is harmonic in \mathbb{R}_+^d (i.e. $\Delta_x K(x, y) = 0$ in \mathbb{R}_+^d)

- Argument from Evans:

$$K(x, y) = -\frac{\partial}{\partial y_d}, \quad \tilde{G}(y-x) = -\frac{\partial}{\partial y_d}(G(y-x) - G(y-\tilde{x}))$$

We know that for all $x \in \mathbb{R}_+^d$, $y \mapsto \tilde{G}(y, x)$ is harmonic in $\mathbb{R}_+^d \setminus \{x\}$. By symmetry we have $\tilde{G}(y, x) = \tilde{G}(x, y)$ for all $x, y \in \mathbb{R}_+^d$. So for all $y \in \mathbb{R}_+^d$, $x \mapsto \tilde{G}(y, x)$ is harmonic in $\mathbb{R}_+^d \setminus \{y\}$. Then for all $y \in \mathbb{R}_+^d$: $-\frac{\partial}{\partial y_d} \tilde{G}(y, x) = K(x, y)$ is harmonic $x \in \mathbb{R}_+^d \setminus \{y\}$. By a limit argument, for all $y \in \partial \mathbb{R}_+^d$, $x \mapsto K(x, y)$ is harmonic for all $x \in \mathbb{R}_+^d$.

- A direct proof:

$$K(x, y) = \frac{2x_d}{d|B_1|} \frac{1}{|x-y|^d}$$

for all $x \in \mathbb{R}_+^d$, $y \in \partial \mathbb{R}_+^d$. For $i \neq d$, $x = (x_1, \dots, x_d)$,

$$\begin{aligned} \partial_{x_i} K(x, y) &= \frac{2x_d}{d|B_1|} \frac{(-d)}{|x-y|^{d+1}} \frac{x_i - y_i}{|x-y|} = \frac{-2x_d}{|B_1|} \frac{x_i - y_i}{|x-y|^{d+2}} \\ \partial_{x_i}^2 K(x, y) &= -\frac{2x_d}{|B_1|} \left[\frac{1}{|x-y|^{d+1}} - \frac{(d+2)}{|x-y|^{d+3}} (x_i - y_i) \frac{(x_i - y_i)}{|x-y|} \right] \\ &= -\frac{2x_d}{|B_1|} \left[\frac{1}{|x-y|^{d+1}} - \frac{(d+2)}{|x-y|^{d+4}} (x_i - y_i)^2 \right] \end{aligned}$$

Moreover:

$$\begin{aligned} \partial_{x_d} K(x, y) &= \frac{2}{d|B_1|} \frac{1}{|x-y|^d} + \frac{2x_d}{d|B_1|} (-d) \frac{(x_d - y_d)}{|x-y|^{d+2}} \\ (y_d = 0) &= \frac{2}{d|B_1|} \frac{1}{|x-y|^d} + \frac{2x_d^2}{|B_1||x-y|^{d+2}} \\ \partial_{x_d}^2 K(x, y) &= \frac{-2}{|B_1|} \frac{(x_d - y_d)}{|x-y|^{d+2}} + \frac{4x_d}{|B_1||x-y|^{d+2}} - \frac{2(d+2)|B_1|^2}{x} \frac{(x_d - y_d)}{d|x-y|^{d+4}} \end{aligned}$$

Then:

$$\begin{aligned}
\Delta_x K(x, y) &= \sum_{i=1}^{d-1} \partial_{x_i}^2 K(x, y) + \partial_{x_d}^2 K(x, y) \\
&= -\frac{2x_d}{|B_1|} \left[\frac{d-1}{|x-y|^{d+2}} - (d+2) \sum_{i=1}^{d-1} \frac{(x_i - y_i)^2}{|x-y|^{d+4}} \right. \\
&\quad \left. + \frac{1+2}{|x-y|^{d+2}} - \frac{(d+2)x_d(x_d - y_d)}{|x-y|^{d+4}} \right] \\
&= -\frac{2x_d}{|B_1|} \left[\frac{d+2}{|x-y|^{d+2}} - (d+2) \frac{1}{|x-y|^{d+4}} \left(\underbrace{\sum_{i=1}^d |x_i - y_i|^2}_{|x-y|^2} \right) \right] = 0
\end{aligned}$$

for all $x \in \mathbb{R}_+^d$, $y \in \partial\mathbb{R}_+^d$. Claim (exercise) for all $x \in \mathbb{R}_+^d$,

$$\int_{\partial\mathbb{R}_+^d} K(x, y) dy = 1$$

Consider

$$u(x) = \int_{\partial\mathbb{R}_+^d} K(x, y) g(y) dy, \quad x \in \mathbb{R}_+^d$$

Since $g \in L^\infty(\mathbb{R}^{d-1}) = L^\infty(\partial\mathbb{R}_+^d)$ and $K(x, y) \geq 0$, hence

$$|u(x)| \leq \left(\int_{\partial\mathbb{R}_+^d} K(x, y) dy \right) \|g\|_{L^\infty}$$

Thus $\|u\|_{L^\infty} \leq \|g\|_{L^\infty}$. Moreover

$$D_x^\alpha u(x) = \int_{\partial\mathbb{R}_+^d} D_x^\alpha K(x, y) g(y) dy$$

bounded, so $u \in C^\infty(\mathbb{R}_+^d)$, $x \mapsto K(x, y)$ is smooth as $x \neq y$.

$$\Delta_x u(x) = \int_{\partial\mathbb{R}_+^d} \underbrace{\Delta_x K(x, y)}_{=0} g(y) dy = 0$$

So u is harmonic in \mathbb{R}_+^d . ($\Rightarrow u \in C^\infty$ by Weyl's lemma). Take $x_0 \in \partial\mathbb{R}_+^d$ and $x \in \mathbb{R}_+^d$. Then:

$$\begin{aligned}
|u(x) - g(x_0)| &= \left| \int_{\partial\mathbb{R}_+^d} K(x, y) (g(y) - g(x_0)) dy \right| \\
&\leq \int_{\partial\mathbb{R}_+^d} K(x, y) |g(y) - g(x_0)| dy \\
&= \underbrace{\int_{|y-x_0| \leq L|x-x_0|}}_{(I)} + \underbrace{\int_{|y-x_0| > L|x-x_0|}}_{(II)}
\end{aligned}$$

$$\begin{aligned}
(I) &= \int_{|y-x_0| \leq L|x-x_0|} K(x, y) |g(y) - g(x_0)| dy \\
&= \sup_{|y-x_0| \leq L|x-x_0|} |g(y) - g(x_0)| \xrightarrow{x \rightarrow x_0} 0 \quad \forall L > 0
\end{aligned}$$

(II): If $|y - x_0| > L|x - x_0|$, then $|y - x| > \frac{1}{2}|y - x_0| > \frac{L}{2}|x - x_0|$ if $L \geq 2$.

$$\begin{aligned} \int_{|y-x_0| > L|x-x_0|} K(x, y) |g(y) - g(x_0)| dy &\leq C \int_{y \in \partial \mathbb{R}_+^d} \frac{x_d}{|x_0 - y|} dy \\ C x_d \int_{\substack{z \in \mathbb{R}^{d-1} \\ |z| > L|x-x_0|}} \frac{1}{|z|^d} dz &= \text{const.} \frac{x_d}{L|x-x_0|} \leq \frac{\text{const.}}{L} \xrightarrow{L \rightarrow \infty} 0 \end{aligned}$$

$$x_d = |x_d - (x_0)_d| \leq |x - x_0|$$

■

5.2 Green's function for a ball

Let $B = B(0, 1)$. For all $x \in B$, for all $y \in \bar{B}$ we want to find the corrector function $\Phi_x(y)$ s.t.

$$\begin{cases} \Delta_y \Phi_x(y) = 0 & \text{in } B \\ \Phi_x(y) = G(y - x) & \text{on } \partial B \end{cases}$$

where for $d \geq 3$: $G(z) = \frac{1}{d(d-2)|B_1||z|^{d-2}}$.

Definition 5.10 (Reflection / Duality through the sphere ∂B) For all $x \in \mathbb{R}^d \setminus \{0\}$ we define $\tilde{x} = \frac{x}{|x|^2}$. Clearly we have for all $x \in B$ that if $|x| < 1$, then $|\tilde{x}| = \left| \frac{x}{|x|^2} \right| = \frac{1}{|x|} > 1$, so $\tilde{x} \notin \bar{B}$

Lemma 5.11 For $d \geq 3$ the function $\Phi_x(y) = G(|x|(y - \tilde{x}))$ is a corrector function.

Proof.

$$\Phi_x(y) = \frac{1}{d(d-2)|B_1||x|^{d-2}|y - \tilde{x}|^{d-2}}$$

for all $x \in B, x \neq 0$, for all $y \in \bar{B}$. Then clearly $y \mapsto \Phi_x(y)$ is harmonic in B (Since $\frac{1}{|z|^{d-2}}$ is harmonic in $\mathbb{R} \setminus \{0\}$). Let's check the boundary: Let $y \in \partial B$, i.e. $|y| = 1$. Then

$$\begin{aligned} ||x|(y - \tilde{x})| &= |x| \left| y - \frac{x}{|x|^2} \right| \\ &= |x| \sqrt{|y|^2 - 2 \frac{xy}{|x|^2} + \left| \frac{x}{|x|^2} \right|^2} \\ &= \sqrt{|x|^2 |y|^2 - 2xy + 1} \\ (|y| = 1) \quad &= \sqrt{|x|^2 - 2xy + |y|^2} = |x - y| \end{aligned}$$

Thus $\Phi_x(y) = G(|x||y - \tilde{x}|) = G(y - x)$ for all $0 \neq x \in B$, for all $y \in \partial B$. Let's compute the Poisson kernel: If want to solve

$$\begin{cases} -\Delta u = 0 & \text{in } B \\ u = g & \text{on } \partial B \end{cases}$$

then

$$u(x) = - \int_{\partial B} \frac{\partial \tilde{G}}{\partial \vec{n}_y}(x, y) g(y) dS(y).$$

$\tilde{G}(x, y) = G(y - x) - \Phi_x(y) = G(y - x) - G(|x|(y - \tilde{x}))$ for all $x \in B \setminus \{0\}$, $y \in \bar{B}$.

$$\frac{\partial \tilde{G}}{\partial \vec{n}_y} = \sum_{i=1}^d \partial_{y_i} \tilde{G} y_i$$

Here

$$\begin{aligned} \partial_{y_i} \tilde{G} &= \partial_{y_i} G(y - x) - \partial_{y_i} [G(|x|(y - \tilde{x}))] \\ &= \frac{-(y_i - x_i)}{d|B_1||y - x|^d} + \frac{y_i - \tilde{x}_i}{d|B_1||x|^{d-2}|y - \tilde{x}|^d} \\ \Rightarrow \frac{\partial \tilde{G}}{\partial \vec{n}_y} &= \sum_{i=1}^d [\dots] y_i \\ &= \frac{-y(y - x)}{d|B_1||y - x|^d} + \frac{y(y - \tilde{x})}{d|B_1||x|^{d-2}|y - \tilde{x}|^d} \\ &= \frac{1}{d|B_1||y - x|^d} (-y(y - x) + y(y - \tilde{x})|x|^2) \\ &= \frac{1}{d|B_1||y - x|^d} [-|y|^2 + xy + |y|^2|x|^2 - xy] \\ &= \frac{-1 + |x|^2}{d|B_1||y - x|^d} \end{aligned}$$

as $y \in \partial B$. ■

Theorem 5.12 (Poisson Formula for a Ball) Let $B = B(0, 1)$, $g \in C(\partial B)$. Define for all $x \in B$:

$$u(x) = \int_{\partial B} K(x, y) g(y) dS(y),$$

$K(x, y) = -\frac{\partial \tilde{G}}{\partial \vec{n}_y}(x, y) = \frac{1 - |x|^2}{d|B_1||y - x|^d}$ for all $x \in B$, for all $y \in \partial B$. Then $u \in C^\infty(B)$, $\Delta u = 0$ and for all $x_0 \in \partial B$ we have $\lim_{x \rightarrow x_0, x \in B} u(x) = g(x_0)$. This holds for all $d \geq 2$.

Proof. We need to check:

1. For all $y \in \partial B$, $x \mapsto K(x, y)$ is harmonic in B .
2. $\int_{\partial B} K(x, y) dS(y) = 1$ for all $x \in B$ (exercise)

Now for all $x \in B$, for all $y \in \partial B$:

$$\begin{aligned}
K(x, y) &= \frac{1 - |x|^2}{d|B_1||y - x|^d} \\
\partial_{x_i} K(x, y) &= \frac{-2x_i}{d|B_1|} \frac{1}{|x - y|^d} - \frac{1 - |x|^2}{|B_1|} \frac{x_i - y_i}{|x - y|^{d+2}} \\
\partial_{x_i}^2 K(x, y) &= -\frac{2}{d|B_1|} \frac{1}{|x - y|^d} + \frac{2x_i}{|B_1|} \frac{x_i - y_i}{|x - y|^{d+2}} + \frac{2x_i}{|B_1|} \frac{x_i - y_i}{|x - y|^{d+2}} \\
&\quad - \frac{1 - |x|^2}{|B_1|} \frac{1}{|x - y|^{d+2}} + \frac{1 + |x|^2}{|B_1|} (d + 2) \frac{(x_i - y_i)^2}{|x - y|^{d+4}} \\
\Delta_x K &= \sum_{i=1}^d \partial_{x_i}^2 K = -\frac{2}{|B_1|} \frac{1}{|x - y|^d} + \frac{4x(x - y)}{|B_1||x - y|^{d+2}} \\
&\quad - \frac{d(1 - |x|^2)}{|B_1|} \frac{1}{|x - y|^{d+2}} + (d + 2) \frac{1 - |x|^2}{|B_1|} \frac{1}{|x - y|^{d+2}} \\
&= \frac{2}{|B_1||x - y|^{d+2}} [-|x|^2 + 2xy - |y|^2 + 2|x|^2 - 2xy + 1 - |x|^2] \\
&= \frac{2}{|B_1||x - y|^{d+2}} [-|x|^2 + 2xy - |y|^2 + 2|x|^2 - 2xy + 1 - |x|^2]
\end{aligned}$$

$1 - |y|^2 = 0$ as $y \in \partial B$. Thus $\Delta_x K(x, y) = 0$, for all $x \in B$, for all $y \in \partial B$.

$$|u(x)| = \left| \int_{\partial B} K(x, y) g(y) dS(y) \right| \leq \|g\|_{L^\infty(\partial B)}$$

$$\int_{\partial B} K(x, y) dS(y) = \|g\|_{L^\infty},$$

$$\Delta_x u(x) = \int_{\partial B} \underbrace{\Delta_x K(x, y)}_{=0} g(y) dS(y) = 0$$

Take $x \in B$, $x \rightarrow x_0 \in \partial B$.

$$\begin{aligned}
|u(x) - g(x_0)| &= \left| \int_{\partial B} K(x, y) (g(y) - g(x_0)) dS(y) \right| \\
&\leq \int_{A_1} + \int_{A_2} K(x, y) |g(y) - g(x_0)| dS(y),
\end{aligned}$$

where

$$\begin{aligned}
A_1 &= \{y \in \partial B \mid |y - x_0| \leq |x - x_0|^\alpha\} \\
A_2 &= \{y \in \partial B \mid |y - x_0| > |x - x_0|^\alpha\}
\end{aligned}$$

On A_1 we have:

$$\int_{A_1} \dots \leq \sup_{\substack{|z - x_0| \leq |x - x_0|^\alpha \\ z \in \partial B}} \int_{\partial B} K(x, y) dS(y) \xrightarrow{x \rightarrow x_0} 0$$

since $G \in C(\partial B)$. On A_2 :

$$\begin{aligned}
&|y - x_0| > |x - x_0|^\alpha \\
\Rightarrow |y - x| &\geq |y - x_0| - |x - x_0| \geq |x - x_0|^\alpha - |x - x_0| \geq \frac{1}{2} |x - x_0|^\alpha
\end{aligned}$$

if $\alpha < 1$ and $|x - x_0|$ small. So we get

$$K(x, y) = \frac{1 - |x|^2}{d|B_1||x - y|^d} \leq C \frac{1 - |x|^2}{|x - x_0|^{d\alpha}} \leq C |x - x_0|^{1-d\alpha}$$

Thus

$$\int_{A_2} K(x, y) |g(y) - g(x_0)| dS(y) \leq C \|g\|_{L^\infty} |x - x_0|^{1-d\alpha} \xrightarrow{x \rightarrow x_0} 0$$

if $1 - d\alpha > 0 \Leftrightarrow \alpha < \frac{1}{d}$. ■

Exercise 5.13 (E 7.2) Define $\mathbb{R}_+^d = \{(x', x_d) \in \mathbb{R}^{d-1} \times \mathbb{R} \mid x_d > 0\}$. Let $K(x, y) = \frac{2x_d}{d|B_1||x-y|^d}$ for all $x \in \mathbb{R}_+^d, y \in \partial\mathbb{R}_+^d = \{(y', 0) \mid y' \in \mathbb{R}^{d-1}\} \simeq \mathbb{R}^{d-1}$. Prove

$$\int_{\partial\mathbb{R}_+^d} K(x, y) dS(y) = 1 \quad \forall x \in \mathbb{R}_+^d$$

Solution. Denote $x = (x', x_d), y = (y', 0), x', y' \in \mathbb{R}^{d-1}, x_d > 0$.

$$\int_{\partial\mathbb{R}_+^d} K(x, y) dS(y) = \int_{\mathbb{R}^{d-1}} \frac{2x_d}{d|B_1|(|x' - y'|^2 + x_d^2)^{\frac{d}{2}}} dy' = \dots$$

as $|x - y| = |(x' - y', x_d)| = \sqrt{|x' - y'|^2 + x_d^2}$.

$$\begin{aligned} (y' - x' \mapsto y') \quad \dots &= \int_{\mathbb{R}^{d-1}} \frac{2x_d}{d|B_1|(|y'|^2 + x_d^2)^{\frac{d}{2}}} dy' \\ (y' = x_d z) &= \int_{\mathbb{R}^{d-1}} \frac{2x_d}{d|B_1|(x_d^2(|z|^2 + 1))^{\frac{d}{2}}} (x_d^{d-1}) dz \\ &= \int_{\mathbb{R}^{d-1}} \frac{2}{d|B_1|(|z|^2 + 1)^{\frac{d}{2}}} dz \\ &= \int_0^\infty \frac{2\omega_{d-1}}{d|B_1|} \frac{1}{(r^2 + 1)^{\frac{d}{2}}} r^{d-2} dr \\ &= \frac{2\omega_{d-1}}{\omega_d} \int_0^\infty \frac{1}{(r^2 + 1)^{\frac{d}{2}}} r^{d-2} dr \end{aligned}$$

Set $d = 2$: $\omega_1 = 1, |\omega_2| = 2\pi$

$$\frac{2}{\pi} \int_0^\infty \frac{1}{r^2 + 1} dr = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} \frac{1}{(\tan t)^2 + 1} [(\tan t)^2 + 1] dt = 1$$

we we set $r = \tan t, t \in (0, \frac{\pi}{2}), \frac{dr}{dt} = (\tan t)' = 1 + (\tan t)^2$ ■

For $d = 3$:

$$\frac{2 \cdot 2\pi}{4\pi} \int_0^\infty \frac{1}{(r^2 + 1)^{\frac{3}{2}}} r dr = \int_0^\infty \frac{d}{dr} \left[\frac{-1}{(r^2 + 1)^{\frac{1}{2}}} \right] dr = \frac{-1}{(r^2 + 1)^{\frac{1}{2}}} \Big|_0^\infty = 1$$

Exercise 5.14 (7.3) Let $g \in C(\partial\mathbb{R}_+^d) \cap L^\infty(\partial\mathbb{R}_+^d)$ ($\partial\mathbb{R}_+^d \simeq \mathbb{R}^{d-1}$).

$$u(x) = \int_{\partial\mathbb{R}_+^d} K(x, y) g(y) dS(y) \quad K(x, y) = \frac{2x_d}{d|B_1||x - y|^d}, x \in \mathbb{R}_+^d$$

Prove that if $g(y) = |y|$, if $|y| \leq 1$, then $|\nabla u|$ is unbounded in $B(0, r) \cap \mathbb{R}_+^d$ for all $r > 0$.

Solution.

$$\begin{aligned}
\partial_{x_d} u(x) &= \int_{\partial \mathbb{R}_+^d} \partial_{x_d} K(x, y) g(y) dy \quad \forall x \in \mathbb{R}_+^d \\
&= \frac{2}{d|B_1|} \int_{\partial \mathbb{R}_+^d} \left[\frac{1}{|x-y|^d} - \frac{dx_d^2}{|x-y|^{d+2}} \right] g(y) dy \\
&= \frac{2}{d|B_1|} \int_{\partial \mathbb{R}_+^d} \frac{1}{|x-y|^{d+2}} [|x-y|^2 - dx_d^2] g(y) dy \\
&= \frac{2}{d|B_1|} \int_{\partial \mathbb{R}_+^d} \frac{1}{(|x'-y'| + x_d^2)^{\frac{d+2}{2}}} [|y'|^2 - (d-1)x_d^2] g(y) dy
\end{aligned}$$

Assume that $\partial_d u$ is bounded in $B(0, r) \cap \mathbb{R}_+^d$. Then:

$$|u(0, x_d) - \underbrace{u(0, 0)}_{g(0)=0}| \leq C|x_d|$$

if x_d small. Consider:

$$\begin{aligned}
\limsup_{x_d \rightarrow 0^+} \frac{u(0, x_d)}{x_d} &= \limsup_{x_d \rightarrow 0^+} c \int_{\mathbb{R}^{d-1}} \frac{1}{(|y'|^2 + x_d^2)^{\frac{d}{2}}} g(y) dy' \\
&\geq \int_{\mathbb{R}^{d-1}} \frac{1}{|y'|^d} g(y) dy = \int_{|y'| \leq 1} + \int_{|y'| > 1} \\
&\text{to } \int_{\mathbb{R}^{d-1}} \frac{1}{|y'|^{d-1}} dy' = \infty
\end{aligned}$$

■

Exercise 5.15 (Bonus 7) Recall the Poisson kernel on a ball $B(0, r) \subseteq \mathbb{R}^d$:

$$K(x, y) = \frac{r^2 - |x|^2}{d|B_1|r} \frac{1}{|x-y|^d}$$

for all $x \in B(0, r)$, $y \in \partial B(0, r)$. Prove:

$$\int_{\partial B(0, r)} K(x, y) dS(y) = 1$$

for all $x \in B(0, r)$. (It suffices if you can prove $d = 2$ and $d = 3$)

5.3 Energy Method

Consider $u \in C^2(\Omega)$ for $\Omega \subseteq \mathbb{R}^d$ open, bounded and with C^1 boundary and

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = g & \text{on } \partial\Omega. \end{cases}$$

Take $\phi \in C_c^\infty(\Omega)$, then by integration by parts:

$$0 = \int_{\Omega} (-\Delta u - f) \phi = \int_{\Omega} \nabla u \nabla \phi - \int_{\Omega} f \phi$$

Key observation: This is the *derivative* of the energy functional

$$E(u) = \frac{1}{2} \int_{\Omega} |\nabla u|^2 - \int_{\Omega} f u$$

If u is a minimizer of E , then it solves the equation $-\Delta u = f$ in Ω . The boundary condition $u = g$ does not appear on E , but this is encoded in the set of *admissible functions*. (The set of candidates of solutions). For the classical solutions, we have

Theorem 5.16 (Dirichlet's principle) Let $\Omega \subseteq \mathbb{R}^d$ be open, bounded with C^1 -boundary. Let $f \in C(\bar{\Omega})$ and $g \in C(\partial\Omega)$. Then the following statements are equivalent:

1. $u \in C^2(\bar{\Omega})$ solves
$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = g & \text{on } \partial\Omega \end{cases}$$
2. u is a minimizer of the variational problem $E = \inf_{v \in A} E(v)$, where

$$E(v) = \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v,$$

$$A = \{v \in C^2(\bar{\Omega}) \mid v = g \text{ on } \partial\Omega\}.$$

Moreover there is at most a solution / minimizer (uniqueness).

Proof. The result holds even for complex-valued functions. Let us write the proof for real-valued functions.

1. \Rightarrow 2.: Let $u \in C^2(\bar{\Omega})$ be a solution of
$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = g & \text{on } \partial\Omega \end{cases}$$
. Then we prove $E(u) \leq E(v)$ for all $v \in A$. If $v \in A$, then $u - v = 0$ on $\partial\Omega$. Using this and $-\Delta u = f$ in Ω , we have:

$$\begin{aligned} 0 &= \int_{\Omega} (-\Delta u - f) \cdot (u - v) dy \\ (\text{Part. Int.}) &= \int_{\Omega} \nabla u (\nabla u - \nabla v) dy - \int_{\Omega} f(u - v) dy \\ &= \left[\frac{1}{2} \int_{\Omega} |\nabla u|^2 dy - \int_{\Omega} f u dy \right] - \left[\frac{1}{2} \int_{\Omega} |\nabla v|^2 dy - \int_{\Omega} f v dy \right] \\ &\quad + \frac{1}{2} \int_{\Omega} |\nabla u|^2 + \frac{1}{2} \int_{\Omega} |\nabla v|^2 \\ &= E(u) - E(v) + \underbrace{\frac{1}{2} \int_{\Omega} |\nabla u - \nabla v|^2}_{\geq 0} \end{aligned}$$

$E(u) \leq E(v)$, so u is a minimizer of $\inf_{v \in A} E(v)$. Moreover u is the unique minimizer on A . Since $E(u) = E(v)$ we have $\int_{\Omega} |\nabla(u - v)|^2 = 0$, so $u - v = \text{const.}$, so $u - v = 0$ in $\bar{\Omega}$.

2. \Rightarrow 1.: Assume that u is a minimizer of $\inf_{v \in A} E(v)$. Then $E(u) \leq E(v)$ for all $v \in A$. Take $\phi \in C_c^\infty(\Omega)$, then $u + t\phi \in A$ for all $t \in \mathbb{R}$.

$$\Rightarrow E(u) \leq E(u + t\phi) \text{ for all } t \in \mathbb{R}$$

$$\Rightarrow t \mapsto E(u + t\phi) \text{ has a minimizer at } t = 0$$

$$\Rightarrow 0 = \frac{d}{dt} E(u + t\phi)|_{t=0}$$

$$= \frac{d}{dt} \left(\frac{1}{2} \int_{\Omega} |\nabla u + t \nabla \phi|^2 - \int_{\Omega} f(u + t\phi) \right) \Big|_{t=0}$$

$$= \frac{d}{dt} \left(\frac{1}{2} \int_{\Omega} |\nabla u|^2 + t^2 |\nabla \phi|^2 + 2t \nabla u \nabla \phi - \int_{\Omega} f(u + t\phi) \right) \Big|_{t=0}$$

$$\int_{\Omega} \nabla u \nabla \phi - \int_{\Omega} f \phi = \int_{\Omega} (-\Delta u - f) \phi$$

for all $\phi \in C_c^\infty(\Omega)$. So $-\Delta u - f = 0$ in Ω and $u = g$ since $u \in A$.

Direct method of calculus of variations. Think $f : \mathbb{R} \rightarrow \mathbb{R}$, $f \in C(\mathbb{R})$, $f(x) \rightarrow \infty$ as $|x| \rightarrow \infty$. There is a $x_0 \in \mathbb{R}$ s.t. $f(x_0) = \inf_{x \in \mathbb{R}} f(x)$.

Step 1: $E = \inf_{x \in \mathbb{R}} f(x) > -\infty$

Step 2: Take a minimizing sequence $\{x_n\} \subseteq \mathbb{R}$, $f(x_n) \rightarrow E$. Up to a subsequence $x_n \rightarrow x_0$ in \mathbb{R} (compactness)

Step 3: Lower semicontinuity $E = \liminf_{n \rightarrow \infty} f(x_n) \geq f(x_0)$

If we apply the direct method to $\inf_{v \in A} E(v)$,

$$E(v) = \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v,$$

$$A = \{v \in C^2(\bar{\Omega}), v = g \text{ on } \partial\Omega\}$$

Step 1: Easy $E = \inf_{v \in A} E(v) > -\infty$

Step 2: There is a minimizing sequence $\{v_n\} \subseteq A$ s.t. $E(v_n) \rightarrow E$. We don't know if there is a subsequence of $\{v_n\}$ that converges to $u \in A$. The lack of compactness is a serious problem! We need to find the right set A ! Consider again

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = g & \text{on } \partial\Omega \end{cases}$$

Consider the simple case $g = 0$. $\Delta u = f$ in $\Omega \Leftrightarrow \nabla u \nabla \phi \dots$ The right set A should be $A = \{v \mid \int_{\Omega} |\nabla v|^2 < \infty, v = 0 \text{ on } \partial\Omega\}$. Rigorously we take $W_0^{1,2}(\Omega) = \overline{C_c^\infty(\Omega)} W^{1,2}(\Omega)$ (Notation: $H_0^1 = W_0^{1,2}$, $H^1 = W^{1,2}$) Recall that $W^{1,p}$ is a Banach space with norm $\|f\|_{W^{1,p}(\Omega)} = \|f\|_{L^p(\Omega)} + \|\nabla f\|_{L^p(\Omega)}$. We know that $C_c^\infty(\Omega)$ is dense in $W_{loc}^{1,p}(\Omega)$, i.e. for all $u \in W_{loc}^{1,p}(\Omega)$ there is $\|u_n\| \leq C_c^\infty$ s.t. $u_n \rightarrow u$ in $W^{1,p}(K)$ for all $K \subseteq \Omega$ compact. However in general $C_c^\infty(\Omega)$ is not dense in $W^{1,p}(\Omega)$, i.e. $W_0^{1,p}(\Omega) = \overline{C_c^\infty(\Omega)} W^{1,p}(\Omega) \subsetneq W^{1,p}(\Omega)$. Clearly $W_0^{1,p}$ is a closed subspace of $W^{1,p}(\Omega) \rightarrow W_0^{1,p}(\Omega)$ is a Banach space with $\|\cdot\|_{W^{1,p}(\Omega)}$. Why does $W_0^{1,p}(\Omega)$ encode the 0-boundary condition? Note that by definition for all $u \in W_0^{1,p}(\Omega)$ there is a sequence $\{u_n\} \subseteq C_c^\infty(\Omega)$, $u_n \rightarrow u$ in $W^{1,p}(\Omega)$ up to a subsequence $u_n(x) \rightarrow u(x)$ for almost every $x \in \Omega$. Note $u_n|_{\partial\Omega} = 0 \rightarrow u|_{\partial\Omega} = 0$ since $\partial\Omega$ must be of 0-measure. ■

Theorem 5.17 (Characterization for $W_0^{1,p}$) Let Ω be open, bounded with C^1 -boundary. Let $u \in W^{1,p}(\Omega) \cap C(\bar{\Omega})$. Then the following statements are equivalent:

- a) $u = 0$ on $\partial\Omega$
- b) $u \in W_0^{1,p}(\Omega)$

(Later we will remove the condition $C(\bar{\Omega})$ by introducing the *Trace operator*.)

Remark 5.18 If $d = 1$, it holds that $W^{1,p} \subseteq C(\bar{\Omega})$. Then the theorem gives a full characterization for $W_0^{1,p}$, but if $d \geq 2$, then in general $W^{1,p} \not\subseteq C(\Omega)$. (later)

Proof of theorem 5.17.

a) \Rightarrow b):

Lemma 5.19 If $u \in W^{1,p}(\Omega)$ and $\text{supp } u \subseteq \Omega$, then $u \in W_0^{1,p}(\Omega)$.

Proof. Since $K := \text{supp } u$ is a compact subset in Ω , we can find a function $\chi \in C_c^\infty(\Omega)$, $\chi = 1$ on K . Moreover since $u \in W^{1,p}(\Omega)$, there is a sequence $\{u_n\} \subseteq C_c^\infty(\Omega)$ s.t. $u_n \rightarrow u$ in $W_{loc}^{1,p}(\Omega)$. We claim that $\chi u_n \rightarrow \chi u$ in $W_{loc}^{1,p}(\Omega)$. (exercise, $\nabla(\chi u) = \nabla \chi u + \chi \nabla u$). This implies $\chi u_n \rightarrow u$ in $W^{1,p}(\text{supp } \chi)$, thus $\chi u_n \rightarrow u$ in $W^{1,p}(\Omega)$, so $u \in W_0^{1,p}(\Omega)$. ■

Assume $u \in W^{1,p}(\Omega) \cap C(\bar{\Omega})$ and $u = 0$ on $\partial\Omega$. Take $G \in C^1(\mathbb{R})$ s.t. $|G(t)| \leq t$ for all t , $G(t) = t$ if $t \geq 2$ and $G(t) = 0$ if $t \leq 1$. Then let

$$\begin{aligned} u_n(x) &:= \frac{1}{n} G(nu(x)) \in W^{1,p}(\Omega) \\ \stackrel{(\text{Chain-rule})}{\Rightarrow} \nabla u_n(x) &= \frac{1}{n} G'(nu(x)) n \nabla u(x) = G'(nu(x)) \nabla u(x) \end{aligned}$$

Moreover, u_n is compactly supported in Ω , so $u_n \in W_0^{1,p}(\Omega)$ by the lemma and $u_n \rightarrow u$ in $W^{1,p}(\Omega)$, so $u \in W_0^{1,p}(\Omega)$ since $W_0^{1,p}$ is a closed space. Recall that $u \in C(\bar{\Omega})$ and $u = 0$ on $\partial\Omega$. Thus for all $\epsilon > 0$ there is a compact $K_\epsilon \subseteq \Omega$ s.t. $\sup_{x \in \Omega \setminus K_\epsilon} |u(x)| \leq \epsilon$. For any given $n \in \mathbb{N}$, $u_n(x) \neq 0$, so $G(nu(x)) \neq 0$. This implies $n|u(x)| > 1$, hence $|u(x)| > \frac{1}{n}$. Thus $u_n(x) = 0$ for all x such that $|u(x)| \leq \frac{1}{n}$, so $\text{supp } u_n \subseteq K_{\frac{1}{n}}$ compact in Ω . Next, let us check $u_n \rightarrow u$ in $W^{1,p}(\Omega)$.

$$\int_{\Omega} |u_n(x) - u(x)|^p dx \rightarrow 0$$

since $u_n(x) = \frac{1}{n} G(nu(x)) \xrightarrow{n \rightarrow \infty} u(x)$ for all $x \in \Omega$ and $|u_n(x)| \leq \frac{1}{n} |G(nu(x))| \leq \frac{1}{n} |nu(x)| \leq |u(x)| \in L^p(\Omega)$.

$$\int_{\Omega} |\nabla u_n(x) - \nabla u(x)|^p dx = \int_{\Omega} |G'(nu(x)) - 1|^p |\nabla u(x)|^p dx \rightarrow 0$$

as $|G'(v(x)) - 1| \rightarrow 0$ for all x s.t. $u(x) \neq 0$ and $\nabla u(x) = 0$ on $\{x \mid u(x) = 0\}$. (exercise)

(b) \Rightarrow (a): Let $u \in W^{1,p}(\Omega) \cap C(\bar{\Omega})$ and $u \in W_0^{1,p}(\Omega)$. Then we prove $u = 0$ on $\partial\Omega$. Lets regard the case $\Omega = Q_+ = \{(x', x_d) \mid \mathbb{R}^{d-1} \times \mathbb{R} \mid |x'| < 1, 0 < x_d < 1\}$. We prove that if $u \in W_0^{1,p}(Q_+) \cap C(\bar{Q}_+)$, then $u = 0$ on $Q_0 = \{(x', 0) \mid x' \in \mathbb{R}^{d-1}, |x'| < 1\}$. Since $u \in W_0^{1,p}(Q_+)$ there is $\{u_n\} \subseteq C_c^\infty(Q_+)$ s.t. $u_n \rightarrow u$ in $W^{1,p}(Q_+)$ for all $x = (x', x_d) \in Q_+$, then:

$$u_n(x', x_d) = \underbrace{u_n(x', 0)}_{=0} + \int_0^{x_d} \partial_d u_n(x', t) dt$$

Hence

$$|u_n(x', x_d)| \leq \int_0^{x_d} |\partial_d u_n(x', t)| dt$$

This implies:

$$\begin{aligned} & \int_{0 < x_d < \epsilon} \int_{|x'| \leq 1} |u_n(x', x_d)| dx' dx_d \\ & \leq \int_{0 < x_d < \epsilon} \int_{|x'| < 1} \left(\int_0^{x_d} |\partial_d u_n(x', t)| dt \right) dx' dx_d \\ & \leq \epsilon \int_{|x'| < 1} \int_0^\epsilon |\partial_d u_n(x', t)| dx' dt \end{aligned}$$

$$\Rightarrow \frac{1}{\epsilon} \int_0^\epsilon \int_{|x'| \leq 1} |u_n(x', x_d)| dx' dx_d \leq \int_0^\epsilon \int_{|x'| < 1} |\partial_d u_n(x', x_d)| dx' dx_d$$

for all $n \in \mathbb{N}$, $\epsilon > 0$. Take now $n \rightarrow \infty$, use $u_n \rightarrow u$ in $W^{1,p}(\Omega)$. Then:

$$\frac{1}{\epsilon} \int_0^\epsilon \int_{|x'| \leq 1} |u(x', x_d)| dx' dx_d \leq \int_0^\epsilon \int_{|x'| < 1} |\partial_d u(x', x_d)| dx' dy$$

for all $\epsilon > 0$. Take $\epsilon \rightarrow 0$:

$$\int_{|x'| \leq 1} |u(x', 0)| dx' \leq 0$$

here we use $u \in C(\bar{\Omega})$ for the left side and Dominated Convergence for the right side. Thus $u(x', 0) = 0$ for all $|x'| \leq 1$, i.e. $u = 0$ on $\partial\Omega$. Let's regard the general case: Let Ω be open, bounded and with C^1 -boundary. Let's define *local charts* By definition for all $x \in \partial\Omega$, there is a U_x open, such there is a bijective map $h : U_x \rightarrow Q$, and h, h^{-1} are C^1 . Then clearly $\partial\Omega \subseteq \bigcup_{x \in \partial\Omega} U_x$. Since $\partial\Omega$ is compact, there is a finite subcover $\{U_i\}_{i=1}^N$ s.t. $\partial\Omega \subseteq \bigcup_{i=1}^N U_i$. We can find U_0 open s.t. $\bar{U}_0 \subseteq \Omega$ and $\Omega \subseteq \bigcup_{i=0}^N U_i$.

Lemma 5.20 There is a sequence $\{\chi_i\}_{i=0}^N \subseteq C^\infty(\mathbb{R}^d)$ s.t.

1. $\chi_i \geq 0$, $\sum_{i=0}^N \chi_i = 1$ in \mathbb{R}^d ($\{\chi_i\}$ is a partition of unity)
2. For all $i = 1, \dots, N$, $\text{supp } \chi_i$ is in U_i , i.e. $\chi_i \in C_c^\infty(U_i)$.
3. $i = 0$, $\text{supp } \chi_0 \subseteq \mathbb{R}^d \setminus \partial\Omega$ and $\chi_0|_\Omega \in C_c^\infty(\Omega)$. (exercise)

Given $u \in W_0^{1,p}(\Omega) \cap C(\bar{\Omega})$. Then $u = \sum_{i=0}^N \chi_i u$, where $\chi_i \geq 0$, $\chi_0 \in C_c^\infty(\Omega)$, $\chi_i \in C_c^\infty(U_i)$. Since $\chi_0 u$ is supported in a compact set inside Ω , $\chi_0 u = 0$ on $\partial\Omega$. It remains to show that for all $i = 1, \dots, N$, $\chi_i u = 0$ on $U_i \cap \partial\Omega$. Then $\chi_i u(h^{-1}x) \in W_0^{1,p}(Q) \cap C(\bar{Q})$. This implies $\chi_i u(h^{-1}x) = 0$ on Q_0 , so $\chi_i u(x) = 0$ on $U_i \cap \partial\Omega$. Why $W_0^{1,p}(U_i \cap \Omega) \rightarrow W_0^{1,p}(Q_+)$. If $v \in W_0^{1,p}(U_i \cap \Omega)$, then $v_n \rightarrow v$, $v_n \in C_c^\infty$. $v_n \circ h^{-1} \rightarrow v \circ h^{-1} \Rightarrow v \circ h^{-1} \in W_0^{1,p}(Q_+)$

■

Exercise 5.21 (E 8.1) Let $u \in W_{loc}^{1,1}(\mathbb{R}^d)$. Let $B = u^{-1}(\{0\})$. Prove that $\nabla u(x) = 0$ for a.e. $x \in B$.

Solution. We have already seen that if $f, g \in W_{loc}^{1,1}(\mathbb{R}^d)$, then $\max(f, g) \in W_{loc}^{1,1}$. This implies that if $u = u^+ - u^- \in W_{loc}^{1,1}$, then $u^+, u^- \in W_{loc}^{1,1}$ since $u^+ = \max(u, 0)$ and $u^- = \max(-u, 0)$. We have that $\nabla u = \nabla u^+ - \nabla u^-$. Claim:

$$\nabla u^+ = \begin{cases} 0 & u(x) \leq 0 \\ \nabla u & u(x) > 0 \end{cases} \quad \nabla u^- = \begin{cases} 0 & u(x) \geq 0 \\ \nabla u & u(x) < 0 \end{cases}$$

$$\begin{aligned} \int_{\mathbb{R}^d} (\partial_i u^+) \phi &= - \int_{\mathbb{R}^d} u^+ \partial_i \phi = - \int_{\{u(x) \leq 0\}} 0 \partial_i \phi - \int_{\{u(x) > 0\}} u \partial_i \phi \\ &= \int_{\{u(x) \leq 0\}} 0 \phi + \int_{\{u(x) > 0\}} \partial_i u \phi \end{aligned}$$

Alternative way: We showed for $f \in W^{1,p}(\mathbb{R}^d)$, that

$$\nabla|f|(x) = \begin{cases} (\nabla f)(x) & f(x) > 0 \\ -(\nabla f)(x) & f(x) < 0 \\ 0 & f(x) = 0 \end{cases}$$

$u_+ = \frac{1}{2}(u + |u|)$. Hence $\nabla u_+ = \frac{1}{2}(\nabla u + \nabla|u|)$. Remark: If $A \subseteq \mathbb{R}$ has measure zero, then $\nabla u 1_{\{u(x) \in A\}} = 0$ a.e. (Th. 6.19 Lieb-Loss Analysis) ■

Exercise 5.22 (E 8.2) Let $\Omega, U \subseteq \mathbb{R}^d$ be open, $U \cap \Omega \neq \emptyset$, $u \in W_0^{1,p}(\Omega)$, $1 \leq p < \infty$, $\chi \in C_c^\infty(U)$. Prove: $\chi u \in W_0^{1,p}(\Omega \cap U)$ Hint: Recall $W_0^{1,p}(\Omega) = \overline{C_c^\infty(\Omega)}^{\|\cdot\|_{W^{1,p}}}$

Solution. By definition there is a sequence $(u_n)_{n \in \mathbb{N}} \subseteq C_c^\infty(\Omega)$ s.t. $u_n \xrightarrow[n \rightarrow \infty]{\|\cdot\|_{W^{1,p}}} u$, i.e.

$$\|u_n - u\|_p + \|\nabla u_n - \nabla u\|_p \xrightarrow{n \rightarrow \infty} 0.$$

Define $f_n : \mathbb{R}^d \rightarrow \mathbb{C}$, $f_n(x) := u_n(x)\chi(x)$. Note $f_n \in C_c^\infty(\Omega \cap U)$ for all $n \in \mathbb{N}$. Claim: $(f_n)_{n \in \mathbb{N}}$ is Cauchy with respect to $\|\cdot\|_{W^{1,p}}$. Proof:

$$\|f_n - f_m\|_p = \|\chi(u_n - u_m)\|_p \leq \|\chi\|_\infty \underbrace{\|u_n - u_m\|_p}_{\xrightarrow[n, m \rightarrow \infty]{} 0} \xrightarrow{n, m \rightarrow \infty} 0$$

$$\nabla f_n = \nabla(\chi u_n) = (\nabla \chi)u_n + \chi \nabla u_n$$

$$\begin{aligned} \|\nabla f_n - \nabla f_m\|_p &\leq \|\nabla \chi(u_n - u_m)\|_p + \|\chi(\nabla u_n - \nabla u_m)\|_p \\ &\leq \|\nabla \chi\|_\infty \underbrace{\|u_n - u_m\|_p}_{\xrightarrow[n, m \rightarrow \infty]{} 0} + \underbrace{\|\chi\|}_{< \infty} \underbrace{\|\nabla u_n - \nabla u_m\|_p}_{\xrightarrow[n, m \rightarrow \infty]{} 0} \xrightarrow{n, m \rightarrow \infty} 0 \end{aligned}$$

Thus, there is a $f \in W_0^{1,p}(\Omega \cap U)$ s.t. $\|f_n - f\|_{W^{1,p}} \xrightarrow{n \rightarrow \infty} 0$. We know:

$$\begin{aligned} \|f_n - \chi u\|_{L^p} &= \|\chi u_n - \chi u\|_p \\ &\leq \|\chi\|_\infty \underbrace{\|u_n - u\|_p}_{\rightarrow 0} \xrightarrow{n \rightarrow \infty} 0 \end{aligned}$$

Since limits in L^p are unique, we get $\chi u = f \in W_0^{1,p}(\Omega \cap U)$. ■

Exercise 5.23 (E 8.3) Let $\Omega, U \subseteq \mathbb{R}^d$ open and bounded, $h : \bar{U} \rightarrow \bar{\Omega}$ C^1 -diffeomorphisms, $u \in W_0^{1,p}(\Omega)$, $1 \leq p < \infty$. Prove $(x \mapsto u(h(x))) \in W_0^{1,p}(U)$.

Solution. Since $u \in W_0^{1,p}(\Omega)$ there is a sequence $(u_n)_{n \in \mathbb{N}} \subseteq C_c^\infty(\Omega)$ s.t.

$$\|u - u_n\|_p + \|\nabla u - \nabla u_n\|_p \xrightarrow{n \rightarrow \infty} 0$$

Define for all $n \in \mathbb{N}$ $f_n : U \rightarrow \mathbb{C}$, $f_n(x) = u_n(h(x))$. Note $f_n \in C_c^1(U)$. Claim 1: $(f_n)_{n \in \mathbb{N}}$ is Cauchy wrt. $\|\cdot\|_{W^{1,p}}$.

$$\begin{aligned} \|f_n - f_m\|_p^p &= \int_U |u_n(h(x)) - u_m(h(x))|^p dx \\ &= \int_\Omega |u_n(y) - u_m(y)|^p dy \underbrace{|\det(Dh^{-1})(y)|}_{\leq C < \infty} \xrightarrow{n, m \rightarrow \infty} 0 \end{aligned}$$

$$(\nabla f_n)(x) = \nabla(u_n(h(x))) = (\nabla u_n)(h(x))(Dh)(x)$$

$$\begin{aligned}
\|\nabla f_n - \nabla f_m\|_p^p &= \int_U |[(\nabla u_n)(h(x)) - (\nabla u_m)(h(x))](Dh(x))|^p dx \\
&\leq C \int_U |(\nabla u_n)(h(x)) - (\nabla u_m)(h(x))|^p dx \\
&= C \int_\Omega |(\nabla u_n)(y) - (\nabla u_m)(y)|^p \underbrace{|\det Dh^{-1}(y)|}_{\leq \tilde{C}} dy \xrightarrow{n,m \rightarrow 0} 0
\end{aligned}$$

Claim 2: $\|f_n - u \circ h\|_p \xrightarrow{n \rightarrow \infty} 0$.

$$\begin{aligned}
\|f_n - u \circ h\|_p &= \int_U |u_n(h(x)) - u(h(x))|^p dx \\
&= \int_\Omega |u_n(y) - u(y)|^p \underbrace{|\det Dh^{-1}(y)|}_{\leq C} dy \xrightarrow{n \rightarrow \infty} 0
\end{aligned}$$

Conclusion: Since $(f_n)_{n \in \mathbb{N}} \subseteq C_c^1(U)$ is Cauchy with respect to $\|\cdot\|_{W^{1,p}}$, there is a $f \in W_0^{1,p}(U)$ s.t. $f_n \xrightarrow{n \rightarrow \infty} f$. Since limits in L^p are unique by claim 2 we get $u \circ h = f \in W_0^{1,p}(U)$. $\|\cdot\|_{W^{1,p}}$ ■

Exercise 5.24 (E 8.4) Let $\Gamma \subseteq \mathbb{R}^d$ be compact, $\{U_i\}_{i=1}^N$ open s.t. $\Gamma \subseteq \bigcup_{i=1}^N U_i$. Prove: There exists $\{\chi_i\}_{i=1}^N \subseteq C^\infty(\mathbb{R}^d)$ s.t.

1. $\chi_i \geq 0$ for all i , $\sum_{i=1}^N \chi_i = 1$
2. $\text{supp}(\chi_i) \subseteq U_i$ for all $i \in \{1, \dots, N\}$
3. $\text{supp}(\chi_0) \subseteq \mathbb{R}^d \setminus \Gamma$

Solution. WLOG assume that $U_i \neq \emptyset$ for all i . If $\Gamma \neq \emptyset$, then $\chi_0 = 1$ does the job. Now suppose $\Gamma \neq \emptyset$. Let $\psi \in C_c^\infty(B_1(0))$, $\psi \geq 0$, $\int \psi = 1$, $\psi|_{B_{\frac{1}{2}}(0)} > 0$ and for $\epsilon > 0$ let $\psi_\epsilon(x) = \frac{1}{\epsilon^d} \psi\left(\frac{x}{\epsilon}\right)$, so $\int \psi_\epsilon = 1$. Define

$$\tilde{d} := \sup\{\tilde{d} > 0 \mid \forall x \in \Gamma \exists i \in \{1, \dots, N\} \text{ s.t. } \text{dist}(x, U_i^c) \geq \tilde{d}\}$$

Claim 1: $\tilde{d} > 0$ Suppose this was not true. Then there is a sequence $(x_n)_{n \in \mathbb{N}} \subseteq \Gamma$ s.t. for all $i \in \{1, \dots, N\}$,

$$\text{dist}(x_n, U_i^c) < \frac{1}{n}$$

Since Γ is compact, there is a subsequence, which we call x_n again, s.t. $x_n \xrightarrow{n \rightarrow \infty} \bar{x}$ for some $\bar{x} \in \Gamma$. By $\Gamma \subseteq \bigcup_{i=1}^N U_i$ there is a $\bar{i} \in \{1, \dots, N\}$ s.t. $B_{\epsilon_{\bar{x}}}(\bar{x}) \subseteq U_{\bar{i}}$. Define $d := \min\{\tilde{d}, 1\} > 0$. For all $\epsilon > 0$, for all $A \subseteq \mathbb{R}^d$: $(A)_\epsilon := \{x \in A \mid \text{dist}(x, A^c) \geq \epsilon\}$. for every $i \in \{1, \dots, N\}$ define $\phi_i : U_i \rightarrow [0, \infty)$ by

$$\phi_i(x) := \mathbb{1}_{(U_i \cap B_R(0))_{\frac{d}{4}}} \star \phi_{\frac{d}{4}}$$

Note $\phi_i \in C_c^\infty(U_i)$ and $(U_i \cap B_R(0))_{\frac{d}{4}} \subseteq (\text{supp}(\phi_i))^0$. Define $\phi_0 : \mathbb{R}^d \setminus \Gamma \rightarrow [0, \infty)$ by $\phi_0(x) = \mathbb{1}_{(\mathbb{R}^d \setminus \Gamma)_{\frac{d}{4}}} \star \psi_{\frac{d}{4}}$. Again, $\phi_0 \in C^\infty(\mathbb{R}^d \setminus \Gamma)$, $\text{supp}(\phi_0)^0 \supseteq (\mathbb{R}^d \setminus \Gamma)_{\frac{d}{4}}$, $\text{supp}(\phi_0) \subseteq \mathbb{R}^d \setminus \Gamma$. Claim 2: For all $x \in \mathbb{R}^d$ there is a $i \in \{0, 1, \dots, N\}$: $\phi_i(x) > 0$. Proof: By construction, we know for $i \in \{1, \dots, N\}$ that ϕ_i is > 0 on $(U_i \cap B_R(0))_{\frac{d}{4}}$. Moreover $\phi_0 > 0$ on $(\mathbb{R}^d \setminus \Gamma)_{\frac{d}{4}}$. thus, we are done if we can show that $\bigcup_{i=1}^N (U_i \cap B_R(0))_{\frac{d}{4}} \cup$

$(\mathbb{R}^d \setminus \Gamma)_{\frac{d}{4}} = \mathbb{R}^d$. Suppose there is a $x \in \mathbb{R}^d \setminus A$. Then $\text{dist}(x, \Gamma) < \frac{d}{4}$. Since $\Gamma \subseteq B_{\frac{R}{2}}(0)$ and $R > 2$ and $d \leq 1$.

$$|x - 0| \leq \text{dist}(x, \Gamma) + \frac{R}{2} < \frac{d}{4} + \frac{R}{2} = R - \frac{d}{4} - \frac{R}{2} + \frac{d}{2} < R - \frac{d}{4} - \frac{2}{2} + \frac{1}{2} < R - \frac{d}{4}$$

Thus $x \in (B_R(c))_{\frac{d}{4}}$. Thus, we are done if we can show that $x \in (U_i)_{\frac{d}{4}}$ for some $i \in \{1, \dots, N\}$. Since $\text{dist}(x, \Gamma) < \frac{d}{4}$, there is a $y \in \Gamma$ s.t. $|x - y| < \frac{d}{4}$. By definition of \tilde{d} there is a $i \in \{1, \dots, N\}$ s.t. $\text{dist}(y, U_i^c) \geq \tilde{d} \geq d$, i.e. for all $z \in U_i^c$ we have $|y - z| \geq d$. We get

$$|x - z| \geq \underbrace{|x - y|}_{< \frac{d}{4}} - \underbrace{|y - z|}_{\geq d} \geq \frac{3d}{4} < \frac{d}{4}$$

This implies $\text{dist}(x, U_i^c) > \frac{d}{4}$, so $x \in (U_i)_{\frac{d}{4}} \not\subset$. Define for all $i \in \{0, \dots, N\}$: $\chi_i : \mathbb{R}^d \rightarrow [0, \infty)$ by

$$\chi_i(x) = \frac{\phi_i(x)}{\sum_{j=0}^N \phi_j(x)}$$

χ_i is well-defined by Claim 2 and $\chi_i \in C^\infty(\mathbb{R}^d)$. Also note that $\sum \chi_i = 1$, $\chi_i \geq 0$, which implies 1. Furthermore, since $\text{supp}(\phi_i) \subseteq U_i$, we have $\text{supp}(\chi_i) \subseteq U_i$ for all $i \in \{1, \dots, N\}$, which implies 2. Finally, since $\text{supp}(\phi_0) \subseteq \mathbb{R}^d \setminus \Gamma$, we get $\text{supp}(\chi_0) \subseteq \mathbb{R}^d \setminus \Gamma$. This implies 3. ■

5.4 Variational problem for weak solutions

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = 0 & \text{on } \partial\Omega \end{cases}$$

("formally") for all $\phi \in C_c^\infty(\Omega)$, then

$$\int_{\Omega} \nabla u \nabla \phi = \int_{\Omega} f \phi$$

if $\nabla u \in L^2$, $f \in L^2$. By a density argument:

$$\int_{\Omega} \nabla u \nabla \phi = \int_{\Omega} f \phi$$

for all $\phi \in \overline{C_c^\infty(\Omega)}^{H^1(\Omega)} = H_0^1(\Omega)$.

Theorem 5.25 (Poincare inequality) There is a $C > 0$ s.t.

$$C \int_{\Omega} |\nabla v|^2 \geq \int_{\Omega} |v|^2$$

for all $v \in H_0^1(\Omega)$.

Remark 5.26 $H^1(\Omega)$ with $\|v\|_{H^1(\Omega)} = (\|v\|_{L^2}^2 + \|\nabla v\|_{L^2}^2)^{\frac{1}{2}}$ is a Hilbert-Space. This implies that $H_0^1(\Omega) \stackrel{(\text{closed})}{\subseteq} H^1(\Omega)$ is also a Hilbert space. By the Poincare inequality (5.25) we have for all $v \in H_0^1(\Omega)$:

$$\|v\|_{H^1(\Omega)} \geq \|\nabla v\|_{L^2} \geq \frac{1}{2C} \|v\|_{L^2} + \frac{1}{2} \|\nabla v\|_{L^2} \geq \frac{1}{C^1} \|v\|_{H^1(\Omega)}$$

We can think of $H_0^1(\Omega)$ as a Hilbert space with $\|v\|_{H_0^1(\Omega)} := \|\nabla v\|_{L^2(\Omega)}$.

Proof. (Of the Poincare inequality (5.25)) We need to prove:

$$\begin{aligned} \exists C > 0 : \quad C \int_{\Omega} |\nabla v|^2 &\geq \int_{\Omega} |v|^2 \quad \forall v \in H_0^1(\Omega) \\ \Leftrightarrow \quad \exists C > 0 : \quad C \int_{\Omega} |\nabla v|^2 &\geq \int_{\Omega} |v|^2 \quad \forall v \in C_c^\infty(\Omega) \end{aligned}$$

Assume by contradiction that this does not hold, i.e. there is no $C > 0$ s.t. the statement holds. Thus there is a sequence $\{v_n\} \subseteq C_c^\infty(\Omega)$ s.t.

$$\int_{\Omega} |v_n|^2 = 1, \quad \int_{\Omega} |\nabla v_n|^2 \xrightarrow{n \rightarrow \infty} 0$$

Since $v_n \in C_c^2(\Omega)$ we can extend v_n by 0 outside Ω , so $v_n \in C_c^\infty(\mathbb{R}^d)$. Then:

$$\int_{\mathbb{R}^d} |v_n|^2 = 1, \quad \int_{\mathbb{R}^d} |\nabla v_n|^2 \rightarrow 0, \quad \text{supp } v_n \subseteq \Omega$$

By the Fourier transform:

$$\int_{\mathbb{R}^d} |\hat{v}_n(k)|^2 dk = 1, \quad \int_{\mathbb{R}^d} |2\pi k|^2 |\hat{v}_n(k)|^2 dk \rightarrow 0, \quad \text{supp } v_n \subseteq \Omega$$

We prove that

$$\int_{\mathbb{R}^d} |\hat{v}_n(k)|^2 dk \rightarrow 0$$

We write

$$\int_{\mathbb{R}^d} |\hat{v}_n(k)|^2 dk = \int_{|k| \leq \epsilon} + \int_{|k| > \epsilon}$$

First, for all $\epsilon > 0$:

$$\int_{|k| > \epsilon} |\hat{v}_n(k)|^2 \leq \int_{\mathbb{R}^d} \frac{|k|^2}{\epsilon^2} |\hat{v}_n(k)|^2 dk \xrightarrow{n \rightarrow \infty} 0$$

Second:

$$\begin{aligned} \int_{|k| \leq \epsilon} |\hat{v}_n(k)|^2 dk &\leq \left(\int_{|k| \leq \epsilon} 1 dk \right)^{\frac{1}{q}} \left(\int_{|k| \leq \epsilon} |\hat{v}_n(k)|^{2p} dk \right)^{\frac{1}{p}}, \quad 1 < p, q < \infty \\ &\leq C \epsilon^{\frac{d}{q}} \|\hat{v}_n\|_{L^{2p}}^2, \quad \frac{1}{p} + \frac{1}{q} = 1 \text{ and } 1 \leq r \leq 2 \end{aligned}$$

Moreover, since Ω is bounded,

$$\|v_n\|_{L^r} \leq \left(\int_{\Omega} |v_n|^r \right)^{\frac{1}{r}} \leq \|1_{\Omega}\|_{L^s} \|v_n\|_{L^2}^{1-\theta} \leq C_{\Omega} \quad \forall 1 \leq r \leq 2.$$

Thus we can take $r < 1$ but close to 1. Then p is sufficiently large, so q is close to 1. Then

$$\int_{|k| \leq \epsilon} |\hat{v}_n(k)|^2 \leq C \epsilon^{\frac{d}{q}} \|\hat{v}_n\|_{L^{2p}}^2 \leq C \epsilon^{\frac{d}{q}} \|v_n\|_{L^r}^2 \leq C \epsilon^{\frac{d}{q}}$$

Conclusion:

$$\int_{\mathbb{R}^d} |\hat{v}_n(k)|^2 = \int_{|k| \leq \epsilon} + \int_{|k| > \epsilon} \leq C \epsilon^{\frac{d}{q}} + \int_{|k| > \epsilon} \xrightarrow{n \rightarrow \infty} C \epsilon^{\frac{d}{q}} \xrightarrow{\epsilon \rightarrow 0} 0$$

which contradicts to the assumption $\|\hat{v}\|_{L^2} = \|v\|_{L^2} = 1$. ■

Exercise 5.27 Let $\Omega \subseteq \mathbb{R}^d$ be open, bounded with C^1 -boundary. Let $u \in W^{1,p}(\Omega)$, for some $1 \leq p < \infty$. Then the following is equivalent:

a) $u \in W_0^{1,p}(\Omega)$

b) $\tilde{u}(x) = \begin{cases} u(x) & x \in \Omega \\ 0 & x \in \mathbb{R}^d \setminus \Omega \end{cases} \in W^{1,p}(\mathbb{R}^d)$

Theorem 5.28 (Dirichlet, Riemann, Poincare, Hilbert) Let $\Omega \subseteq \mathbb{R}^d$ be open, bounded with C^1 -boundary. Let $f \in L^2(\Omega)$. Then there exists a unique solution $u \in H_0^1(\Omega)$ of the variational problem

$$\int_{\Omega} \nabla u \nabla \phi = \int_{\Omega} f \phi$$

for all $\phi \in H_0^1(\Omega)$. ($\Rightarrow -\Delta u = f$ in $D'(\Omega)$). Moreover, u is the unique minimizer of

$$\inf_{v \in H_0^1(\Omega)} \left(\frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v \right)$$

Proof. Let us prove that there is a solution $u \in H_0^1(\Omega)$ for $\inf_{v \in H_0^1(\Omega)} E(v)$, $E(v) = \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v$.

Step 1: We prove $E > -\infty$. Take $v \in H_0^1(\Omega)$. By the Poincare and Hölder inequalities:

$$\begin{aligned} E(v) &= \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v \\ &\geq \frac{1}{2C} \|v\|_{L^2(\Omega)} - \|f\|_{L^2(\Omega)} \|v\|_{L^2(\Omega)} \\ &\geq \frac{1}{2C} \|v\|_{L^2(\Omega)}^2 - \left(\frac{1}{4C} \|v\|_{L^2(\Omega)}^2 + C \|f\|_{L^2(\Omega)}^2 \right) \\ &\geq -C \|f\|_{L^2(\Omega)}^2 > -\infty \end{aligned}$$

We can also bound:

$$\begin{aligned} E(v) &= \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v \\ &\geq \frac{1}{4} \int_{\Omega} |\nabla v|^2 - \frac{1}{4C} \int_{\Omega} |v|^2 - \|f\|_{L^2} \|v\|_{L^2} \\ &\geq \frac{1}{4} \int_{\Omega} |\nabla v|^2 - C \|f\|_{L^2}^2 \end{aligned}$$

Step 2: We can take a minimizing sequence $\{v_n\} \subseteq H_0^1(\Omega)$ s.t. $E(v_n) \xrightarrow{n \rightarrow \infty} E$. Then:

$$\frac{1}{4} \int_{\Omega} |\nabla v_n|^2 \leq E(v_n) + C \|f\|_{L^2}^2 \longrightarrow \text{const.}$$

So $|\nabla v_n|$ is bounded in $L^2(\Omega)$. We know that $H_0^1(\Omega)$ is a Hilbert space with norm $\|v\|_{H_0^1(\Omega)} = \|\nabla v\|_{L^2(\Omega)}$ (and the norm is equivalent to the H^1 -norm). Thus $\{v_n\}$ is bounded in $H_0^1(\Omega)$.

Remark 5.29 (Reminder from functional analysis) Let H be a Hilbert space. We say that $v_n \rightarrow v$ if $\|v_n - v\| \rightarrow 0$ and $v_n \rightarrow v$ weakly in H if $\langle v_n, \phi \rangle \rightarrow \langle v, \phi \rangle$ for all $\phi \in H$.

Theorem 5.30 (Banach-Alaoglu) If H is a Hilbert space and $\{v_n\}$ is a bounded sequence, then there is a subsequence $\{v_{n_k}\}$ s.t. $v_{n_k} \rightarrow v$ weakly in H .

Remark 5.31 – $v_n \rightarrow v$ in H iff $f(v_n) \rightarrow f(v)$ for all $f \in H^* = \mathcal{L}(H, \mathbb{R})$.

– If $v_n \rightarrow v$ in H , then: $\liminf_{n \rightarrow \infty} \|v_n\| \geq \|v\|$ (Fatous Lemma)

In fact, for all $\phi \in H$ $\langle v_n, \phi \rangle \rightarrow \langle v, \phi \rangle$ and $|\langle v_n, \phi \rangle| \leq \|v_n\| \|\phi\|$. This implies

$$\frac{|\langle v, \phi \rangle|}{\|\phi\|} \leq \liminf_{n \rightarrow \infty} \|v_n\|.$$

So we get

$$\|v\| = \sup_{\phi \neq 0} \frac{|\langle v, \phi \rangle|}{\|\phi\|} \leq \liminf_{n \rightarrow \infty} \|v_n\|$$

By the Banach-Alaoglu theorem, up to a subsequence, $v_n \rightarrow u$ weakly in $H_0^1(\Omega)$. We prove that u is a minimizer for \mathcal{E}

$$E \leftarrow \mathcal{E}(v_n) = \frac{1}{2} \int |\nabla v_n|^2 - \int f v_n$$

– Since $v_n \rightarrow u$ in $H_0^1(\Omega)$ we have that

$$\liminf_{n \rightarrow \infty} \|v_n\|_{H_0^1(\Omega)}^2 \geq \|u\|_{H_0^1(\Omega)}^2$$

So we have

$$\liminf_{n \rightarrow \infty} \int_{\Omega} |\nabla v_n|^2 \geq \int_{\Omega} |\nabla u|^2.$$

– Consider the functional $\mathcal{L} : \phi \in H_0^1(\Omega) \rightarrow \int_{\Omega} f \phi$. We claim that \mathcal{L} is continuous. In fact:

$$|\mathcal{L}| = \left| \int_{\Omega} f \phi \right| \leq \|f\|_{L^2} \|\phi\|_{L^2} \leq C \|f\|_{L^2} \|\nabla f\|_{L^2} = C \|f\|_{L^2} \|\phi\|_{H_0^1(\Omega)}$$

Thus from $v_n \rightarrow v$ in $H_0^1(\Omega)$ we get $\mathcal{L}(v_n) \rightarrow \mathcal{L}(u)$, thus $\int_{\Omega} f v_n \rightarrow \int_{\Omega} f u$.

Conclusion: $E = \liminf \mathcal{E}(v_n) \geq \mathcal{E}(u)$, so u is a minimizer for \mathcal{E} .

Step 3: Uniqueness. If E has 2 minimizers u_1, u_2 we can prove that $u_1 = u_2$. This is because of the convexity:

$$\begin{aligned} 0 &\geq \frac{\mathcal{E}(u_1) + \mathcal{E}(u_2)}{2} - \mathcal{E}\left(\frac{u_1 + u_2}{2}\right) \\ &= \frac{1}{8} \left[2 \int_{\Omega} |\nabla u_1|^2 + 2 \int_{\Omega} |\nabla u_2|^2 - \int_{\Omega} |\nabla(u_1 + u_2)|^2 \right] \\ &= \frac{1}{8} \int_{\Omega} |\nabla u_1 - \nabla u_2|^2 \geq 0 \end{aligned}$$

This implies that $\nabla(u_1 - u_2) = 0$, so $u_1 - u_2 = \text{const} = c_0$. Since $u_1, u_2 \in H_0^1(\Omega)$, we have that $u_1 - u_2 \in H_0^1(\Omega)$ and $c_0 \in C(\bar{\Omega})$. Hence $c_0 = 0$ on $\partial\Omega$, so $c_0 = 0$. \blacksquare

Remark 5.32 We can also prove directly that there is a unique $u \in H_0^1(\Omega)$ s.t.

$$\int_{\Omega} \nabla u \nabla \phi = \int_{\Omega} f \phi \quad \forall \phi \in H_0^1(\Omega)$$

by Riesz theorem. So we get $\langle u, \phi \rangle_{H_0^1(\Omega)} = \mathcal{L}(\phi)$.

Recall the corrector function for the unit ball:

$$\phi_x(y) = G(|x||y - \tilde{x}|), \quad \tilde{x} = \frac{x}{|x|^2}$$

This is ok if $x \neq 0$. When $x \rightarrow 0$:

$$G(|x|(y - \tilde{x})) = G(\underbrace{|x|y - \frac{x}{|x|}}_{|\cdot| \rightarrow 1})G(z), \quad |z| = 1$$

is well-defined as G is radial.

Question: If $u \in H^1(\Omega)$, then how can we define $u|_{\partial\Omega}$?

5.5 Theory of Trace

Theorem 5.33 (Trace Operator) Let $\Omega \subseteq \mathbb{R}^d$ be open, bounded with C^1 boundary. Then there is a unique linear bounded operator $T : H^1(\Omega) \rightarrow L^2(\partial\Omega)$ such that

- If $u \in H^1(\Omega) \cap C(\bar{\Omega})$, then $Tu = u|_{\partial\Omega}$ in the usual restriction sense.
- There is a $C > 0$ s.t. $\|Tu\|_{L^2(\partial\Omega)} \leq C\|u\|_{H^1(\Omega)}$ for all $u \in H^1(\Omega)$

Theorem 5.34 If $u \in H^1(\Omega)$, then $u \in H_0^1(\Omega)$ is equivalent to $Tu = 0$ in $L^2(\partial\Omega)$. ($H_0^1(\Omega) = T^{-1}(\{0\})$). Then we can discuss about

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u|_{\partial\Omega} = g & \text{on } \partial\Omega \end{cases}$$

Lemma 5.35 (Trace inequality on \mathbb{R}_+^d) if $u \in C_c^\infty(\mathbb{R}^d)$, then:

$$\|u|_{\partial\mathbb{R}_+^d}\|_{L^2(\partial\mathbb{R}_+^d)} \leq C\|u\|_{H^1(\mathbb{R}^d)} \quad \text{with } C > 0 \text{ independent of } u.$$

Proof. $x = (x', x_d) \in \mathbb{R}^{d-1} \times \mathbb{R}$.

$$\begin{aligned} |u(x', 0)|^2 &= - \int_0^\infty \partial_d (|u(x', x_d)|^2) dx_d \\ &= - \int_0^\infty 2\partial_d u(x', x_d) u(x', x_d) dx_d \\ &\leq \int_0^\infty [|\partial_d u(x', x_d)|^2 + |u(x', x_d)|^2] dx_d \end{aligned}$$

This implies:

$$\begin{aligned} \int_{\mathbb{R}^{d-1}} |u(x', 0)|^2 dx' &\leq \int_{\mathbb{R}^{d-1}} \left(\int_0^\infty [\dots] dx_d \right) dx' \\ &= \int_{\mathbb{R}_+^d} [|\partial_d u|^2 + |u|^2] = \|u\|_{H^1(\mathbb{R}_+^d)}^2 \end{aligned}$$

■

Corollary 5.36 If $u \in H^1(Q)$ and u is compactly supported, then:

$$\|u\|_{L^2(Q_0)} \leq \|u\|_{H^1(Q_+)}$$

Here

$$\begin{aligned} Q &= \{x = (x', x_d) \in \mathbb{R}^{d-1} \times \mathbb{R} \mid |x'| < 1, |x_d| < 1\} \\ Q_+ &= \{x = (x', x_d) \in Q \mid x_d > 0\} \\ Q_0 &= \{x = (x', x_d) \in Q \mid x_d = 0\}. \end{aligned}$$

Proof. We extend u by 0 outside of Q , so $u \in H^1(\mathbb{R}^d)$. ■

Theorem 5.37 (Extension) If $\Omega \subseteq \mathbb{R}^d$ is open, bounded with C^1 -boundary, then there is a bounded linear operator $B : H^1(\Omega) \rightarrow H^1(\mathbb{R}^d)$ s.t.

- $Bu|_\Omega = u$ for all $u \in H^1(\Omega)$
- $\|Bu\|_{H^1(\mathbb{R}^d)} \leq C\|u\|_{H^1(\Omega)}$ and $\|Bu\|_{L^2(\mathbb{R}^d)} \leq C\|u\|_{L^2(\Omega)}$.

Proof of Theorem 5.37. Since $\partial\Omega$ is C^1 there are open sets $\{U_i\}_{i=1}^N \subseteq \mathbb{R}^d$ such that $\partial\Omega \subseteq \bigcup_{i=1}^N U_i$ and for all i there is a C^1 -diffeomorphism $h_i : U_i \rightarrow Q$ s.t. $h_i(U_i) = Q$, $h_i(U_i \cap \Omega) = Q_+$, $h_i(U_i \cap \partial\Omega) = Q_0$. Then there exists a partition of unity $\{\theta_i\}_{i=1}^N \subseteq C^\infty(\mathbb{R}^d)$ s.t.

1. $\sum_{i=1}^N \theta_i = 1$ for all $x \in \mathbb{R}^d$
2. For all $i = 1, \dots, N$: $\theta_i \in C_c^\infty(U_i)$
3. $\text{supp } \theta_0 \subseteq \mathbb{R}^d \setminus \partial\Omega$ (in particular $\theta_0|_\Omega \in C_c^\infty(\Omega)$)

Then given $u \in H^1(\Omega)$, we can write $u = \sum_{i=1}^N \theta_i u$, where $u_i = \theta_i u$. By the extension theorem (5.37), $u \rightarrow$ extended to $Bu \in H^1(\mathbb{R}^d)$, thus

$$Bu = \sum_{i=1}^N \theta_i(Bu) = \sum_{i=1}^N v_i, \quad v_i = \theta_i(Bu)$$

Then $v_i \in H^1(\mathbb{R}^d)$ and v_i is compactly supported in U_i for all $i = 1, 2, \dots, N$ and $\text{supp } v_0 \subseteq \mathbb{R}^d \setminus \partial\Omega$, $v_i \in H^1(\mathbb{R}^d)$ and compactly supported inside U_i . This implies $\tilde{v}_i(y) = v_i(h_i^{-1}(y)) \in H^1(Q)$ and compactly supported inside Q , $y \in Q$. Thus $\|\tilde{v}_i\|_{L^2(Q_0)} \leq C\|\tilde{v}_i\|_{H^1(Q_+)}$. So we have $\|v_i\|_{L^2(\partial\Omega)} \leq C\|\tilde{v}_i\|_{L^2(Q_0)} \leq C'\|\tilde{v}_i\|_{H^1(Q_+)} \leq C''\|v_i\|_{H^1(U_i \cap \Omega)}$. Thus:

$$\begin{aligned} \|u\|_{L^2(\partial\Omega)} &= \left\| \sum_{i=1}^N v_i \right\|_{L^2(\partial\Omega)} \leq \sum_{i=1}^N \|v_i\|_{L^2(\partial\Omega)} \leq \sum_{i=1}^N C'' \|v_i\|_{H^1(U_i \cap \Omega)} \\ &= C'' \sum_{i=1}^N \|\theta_i u\|_{H^1(\Omega)} \leq C'' \sum_{i=1}^N C \|u\|_{H^1(\Omega)} \end{aligned}$$

This proof works for $u \in C(\bar{\Omega})$. This implies

$$\|u\|_{L^2(\partial\Omega)} \leq C\|u\|_{H^1(\Omega)} \quad \text{for all } u \in H^1(\Omega) \cap C(\bar{\Omega}).$$

This allows us to define

$$\begin{aligned} T : H^1(\Omega) &\longrightarrow L^2(\partial\Omega) \\ u &\longmapsto u|_{\partial\Omega} \end{aligned}$$

by continuity. I.e. for all $u \in H^1(\Omega)$ there is $\{u_n\} \subseteq H^1(\Omega) \cap C(\bar{\Omega})$ s.t. $u_n \rightarrow u$ in H_0^1 . Then $Tu_n \rightarrow Tu$ in $L^2(\partial\Omega)$. ■

Lemma 5.38 (Extension for Q) Let $u \in H^1(Q_+)$. Then we define $Bu : Q \rightarrow \mathbb{R}$ by

$$Bu(x) = \begin{cases} u(x) & x \in Q_+ \\ -u(x', -x_d) & x \in Q_- \end{cases},$$

$x = (x, x_d)$. Then $Bu \in H^1(Q)$ and $Bu|_{Q_+} = u$, $\|Bu\|_{L^2(Q)}^2 = 2\|u\|_{L^2(Q_+)}^2$, $\|\nabla(Bu)\|_{L^2(Q)}^2 = \|\nabla u\|_{L^2(Q_+)}^2$

Proof. It is obvious $Bu|_{Q_+} = u$ and

$$\begin{aligned} \int_Q |Bu|^2 &= \int_{Q_+} |Bu|^2 + \int_{Q_-} |Bu|^2 \\ &= \int_{Q_+} |u|^2 + \int_{Q_- = \{(x, -x_d) | (x, x_d) \in Q_+\}} |u(x, -x_d)|^2 \\ &= 2 \int_{Q_+} |u|^2 \end{aligned}$$

We prove:

$$\nabla(Bu)(x) = \begin{cases} \nabla u(x) & u \in Q_+ \\ \nabla u(x', -x_d) & u \in Q_- \end{cases}$$

First, $\partial_d Bu(x) = \partial_d u(x', -x_d)$ if $x \in Q_-$. Take $\phi \in C_c^\infty(Q)$, then:

$$\begin{aligned} \int_Q (Bu(x))(\partial_d \phi)(x) dx &= \int_{Q_+} u \partial_d \phi + \int_{Q_-} -u(x', -x_d) \partial_d [\phi(x', x_d)] dx \\ (x \rightarrow -x_d) &= \int_{Q_+} u \partial_d \phi + \int_{Q_+} [u(x', x_d)(\partial_d \phi)(x', -x_d)] dx \\ &\stackrel{(\phi \notin C_c^\infty(Q_+))}{\approx} \int_{Q_+} (\partial_d u) \phi(x) + \int_{Q_+} (\partial_d u(x', x_d)) \phi(x', -x_d) dx \\ &= - \int_{Q_+} (\partial_d u) \phi(x) + \int_{Q_-} \partial_d u(x', -x_d) \phi(x', x_d) dx \\ &= - \int_Q f \phi, \quad \text{where } f(x) = \begin{cases} \partial_d u & x \in Q_+ \\ -\partial_d u(x', -x_d) & x \in Q_- \end{cases} \end{aligned}$$

We prove $\int_{Q_+} u \partial_d \tilde{\phi} = - \int_{Q_+} (\partial_d u) \tilde{\phi}$ where $\tilde{\phi}(x, x_d) = \phi(x, x_d) - \phi(x, -x_d)$, $\tilde{\phi} \notin C_c^\infty(Q_+)$. Define $\eta_\epsilon = 0$ when $|x_d| \leq \epsilon$, $\eta_\epsilon = 1$ if $|x_d| \geq 2\epsilon$, $\eta_\epsilon \in C^\infty$, $\eta_\epsilon(x', x_d) = \eta_0(x', \frac{x_d}{\epsilon})$, $\eta_0 = \begin{cases} 1 & |x_d| \geq 2 \\ 0 & |x_d| \leq 1 \end{cases}$. We have

$$\int_{Q_+} u \partial_d (\eta_\epsilon \tilde{\phi}) = - \int_{Q_+} \partial_d u (\eta_\epsilon \tilde{\phi})$$

We take $\epsilon \rightarrow 0$,

$$\int_{Q_+} (\partial_d u) (\eta_\epsilon \tilde{\phi}) \rightarrow \int_{Q_+} (\partial_d u) \tilde{\phi}$$

by dominated convergence.

$$\begin{aligned} \int_{Q_+} u \partial_d (\eta_\epsilon \tilde{\phi}) &= \int_{Q_+} u (\partial_d \eta_\epsilon) \tilde{\phi} + \int_{Q_+} u \eta_\epsilon \partial_d \tilde{\phi} \\ &\xrightarrow{\epsilon \rightarrow 0} \int_{Q_+} u \partial_d \tilde{\phi} \end{aligned}$$

by dominated convergence.

$$\begin{aligned}
& \left| \int_{Q_+} u(\partial_d \eta_\epsilon) \tilde{\phi} \right| = \left| \int_Q u \frac{1}{\epsilon} (\partial_d \eta_0) \left(x, \frac{x_d}{\epsilon} \right) \tilde{\phi} \right| \\
& \begin{pmatrix} |\tilde{\phi}(x', x_d)| \\ = |\phi(x, x_d) - \phi(x, x_d)| \\ \leq \|\partial_d \phi\|_{L^\infty} |x_d| \end{pmatrix} \leq \frac{1}{\epsilon} \|\partial_d \eta_0\|_{L^\infty} \int_{Q_+ \cap \{x_d \leq 2\epsilon\}} |u| \underbrace{|\tilde{\phi}|}_{\leq C|x_d| \leq C\epsilon} \\
& (\text{Dominated cv } u \in L^1(Q_+)) \leq C \int_{Q_+ \cap \{0 < x_d \leq 2\epsilon\}} |u| \xrightarrow{\epsilon \rightarrow 0} 0
\end{aligned}$$

where $u \in L^2(Q_+)$ because $u \in H^1(Q_+)$. ■

Exercise 5.39 (E. 9.1) Let Ω be open, bounded with C^1 -boundary. Let $u \in H_0^1(\Omega)$, $f \in L^2(\Omega)$. Show that the following statements are equivalent:

- 1) $-\Delta u = f$ in $D'(\Omega)$
- 2) $\int \nabla u \nabla \phi = \int f \phi$ for all $\phi \in H_0^1$
- 3) $E = \inf_v \left(\frac{1}{2} \int_\Omega |\nabla v|^2 - \int_\Omega f v \right)$

Solution.

1) \Rightarrow 2) From $-\Delta u = f$ in $D'(\Omega)$ we get that

$$\int_\Omega u(-\Delta \phi) = \int_\Omega f \phi$$

for all $\phi \in C_c^\infty(\Omega)$. Claim: If $u \in H_0^1$, $\phi \in C_c^\infty$, then

$$\int_\Omega (-\Delta \phi) = \int_\Omega \nabla u \nabla \phi$$

Density argument: $u \in H_0^1 = \overline{C_c^\infty(\Omega)}^{\|\cdot\|_H}$, so there is a sequence $\{u_n\} \subseteq C_c^\infty(\Omega)$ s.t. $u_n \rightarrow u$ in $H^1(\Omega)$. Since $u_n, \phi \in C_c^\infty(\Omega)$, then by the integration by parts:

$$\int_\Omega u_n(-\Delta \phi) = \int_\Omega (\nabla u_n) \nabla \phi \forall n$$

Take $n \rightarrow \infty$, then,

$$\int_\Omega u(-\Delta \phi) = \int_\Omega (\nabla u) \nabla \phi$$

as $u_n \rightarrow u$ and $\nabla u_n \rightarrow \nabla u$ in L^2 . Claim: If $\int_\Omega \nabla u \nabla \phi = \int_\Omega f \phi$ for all $\phi \in C_c^\infty(\Omega)$, then

$$\int_\Omega \nabla u \nabla \phi = \int_\Omega f \phi$$

for all $\phi \in H_0^1$. (Given $\nabla u, f \in L^2$). With density argument: For all $\phi \in H_0^1$ there is a sequence $\{\phi_n\} \subseteq C_c^\infty(\Omega)$ s.t. $\phi_n \rightarrow \phi$ in H^1 . Then:

$$\int_\Omega \nabla u \nabla \phi_n = \int_\Omega f \phi_n$$

for all n . Take $n \rightarrow \infty$:

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

as $\phi_n \rightarrow \phi$, $\nabla \phi_n \rightarrow \nabla \phi$ in L^2 .

2) \Rightarrow 3) We show $E(u) \leq E(v)$ for all $v \in H_0^1$, i.e.

$$\frac{1}{2} \int_{\Omega} |\nabla u|^2 - \int_{\Omega} f u \leq \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v$$

for all $v \in H_0^1$. Write $v = u + w$, then:

$$\begin{aligned} E(v) &= \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v \\ &= \frac{1}{2} \int_{\Omega} |\nabla(u+w)|^2 - \int_{\Omega} f(u+w) \\ &= \frac{1}{2} \int_{\Omega} [|\nabla u|^2 + |\nabla w|^2 + 2\nabla u \nabla w] \int_{\Omega} (f u + f w) \\ &= E(u) + \frac{1}{2} \int_{\Omega} |\nabla w|^2 + \underbrace{\left(\int_{\Omega} \nabla u \nabla w - \int_{\Omega} f w \right)}_{=0} \end{aligned}$$

as $w = v - u \in H_0^1$ (by (2))

3) \Rightarrow 1)

$$E(u) \leq E(u + t\phi)$$

for all $\phi \in H_0^1$ (or C_c^∞) for all $t \in \mathbb{R}$. This implies:

$$\frac{d}{dt} E(u + t\phi)|_{t=0} = 0$$

Here

$$\begin{aligned} E(u + t\phi) &= \frac{1}{2} \int_{\Omega} \underbrace{|\nabla(u + t\phi)|^2}_{|\nabla u|^2 + t^2 |\nabla \phi|^2 + 2t \nabla u \nabla \phi} - \int_{\Omega} f(u + t\phi) \\ &= E(u) + t \left[\int_{\Omega} \nabla u \nabla \phi \int_{\Omega} f \phi \right] + t^2 \int_{\Omega} |\nabla \phi|^2 \end{aligned}$$

This implies

$$\frac{d}{dt} E(u + t\phi)|_{t=0} = \int_{\Omega} \nabla u \nabla \phi - \int_{\Omega} f \phi$$

Conclude:

$$\int_{\Omega} \nabla u \nabla \phi = \int_{\Omega} f \phi$$

for all $\phi \in H_0^1$ or C_c^∞ . So we get

$$\int_{\Omega} u(-\Delta \phi) = \int_{\Omega} f \phi$$

for all $\phi \in C_c^\infty$. so we can conclude:

$$-\Delta u = f$$

in $D'(\Omega) \Rightarrow 1)$

■

Exercise 5.40 (E 9.2)

$$Q = \{(x', x_d) \mid |x'| < 1, |x_d| < 1\}$$

Given $u \in H^1(Q_+)$, define $Bu : Q \rightarrow \mathbb{R}$ as

$$Bu(x) = \begin{cases} u(x) & x \in Q_+ \\ u(\tilde{x}) & x \in Q_- \end{cases},$$

$x = (x', x_d) \Leftrightarrow \tilde{x} = (x', -x_d)$, $x \in Q_- \Leftrightarrow \tilde{x} \in Q_+$. In the lectures:

$$\partial_d(Bu)(x) = \begin{cases} \partial_d u(x) & x \in Q_+ \\ -(\partial_d u)(\tilde{x}) & x \in Q_- \end{cases}$$

This implies $\partial_d(Bu) \in L^2(Q)$.

1. For all $i = 1, \dots, d-1$, then:

$$\partial_i(Bu)(x) = \begin{cases} \partial_i u(x) & x \in Q_+ \\ \partial_i u(\tilde{x}) & x \in Q_- \end{cases}$$

2. Example $u \in H^2(Q_+)$ but $Bu \notin H^2(Q)$.

Solution. 1. For all $\phi \in C_c^\infty(Q)$:

$$\int_Q Bu(x) \partial_i \phi(x) dx = \int_{Q_+} u(x) \partial_i \phi(x) dx + \int_{Q_-} u(\tilde{x}) \partial_i \phi(x) dx$$

Write $\vec{n} = (n_1, \dots, n_d)$. Here:

$$\begin{aligned} \int_{Q_+} u(x) \partial_i \phi(x) dx &= \int_{Q_+} -\partial_i u(x) \phi(x) dx + \int_{\partial Q_+} u(x) \phi(x) n_i dS \\ \int_{Q_-} u(x', -x_d) \partial_i \phi(x', x_d) dx' dx_d &= - \int_{Q_+} u(x', x_d) \partial \phi(x', -x_d) dx' dx_d \\ &= \int_{Q_+} \partial_i u(x) \phi(\tilde{x}) - \int_{\partial Q_+} u \phi n_i dS \\ &= \int_{Q_-} -\partial_i u(\tilde{x}) \phi(x) - \int_{\partial Q_+} u \phi n_i dS \end{aligned}$$

with $d(-x_d) = d(x_d)$. Conclude:

$$\begin{aligned} \int_Q (Bu)(x) \partial_i \phi(x) dx &= \int_{Q_+} (-\partial_i u)(x) \phi(x) + \int_{Q_-} (-\partial_i u)(\tilde{x}) \phi(x) \\ &= \int_Q -h(x) \phi(x) dx, \quad h(x) = \begin{cases} \partial_i u(x), & x \in Q_+ \\ \partial_i u(\tilde{x}), & x \in Q_- \end{cases} \end{aligned}$$

for all $\phi \in C_c^\infty(Q)$, so $\partial_i(Bu) \in L^2$ for all $i = 1, 2, \dots, d-1$. Thus $Bu \in H^1(Q)$.

2. 1D: Take $Q_+(0, 1)$, $Q_- = (-1, 0)$, $Q_0 = \{0\}$, $Q = (-1, 1)$, $u(x) = x$ in $Q_+ = (0, 1)$, $Bu(x) = u(x) = -x$ if $x \in Q_- = (-1, 0)$, i.e. $Bu(x) = |x|$ if $x \in Q = (-1, 1)$. We know

$$(Bu)'(x) = \begin{cases} 1 & x \in (0, 1) \\ -1 & x \in (-1, 0) \end{cases} \in L^2(-1, 1)$$

i.e. $Bu \in H^1(Q)$.

$$(Bu)''(x) = 2\delta_0(x)$$

in $D'(Q)$ but $\notin L^2(-1, 1)$, i.e. $Bu \notin H^2(Q)$. Question: Given $u \in H^2(Q_+)$, can we find an extension $Bu \in H^2(Q)$ Yes! E.g. $u(x) = x$ in $(0, 1)$, so $Bu(x) = x$ in $(-1, 1)$. In general: $u \in H^2(Q) \rightsquigarrow \tilde{u} \in H^2(Q)$ but $\nabla u = 0$ on ∂Q_+ . ■

Exercise 5.41 (Bonus 8) Assume $u \in H^2(Q_+)$ and $\begin{cases} u = 0 \\ \nabla u = 0 \end{cases}$ on ∂Q_+ . Prove that $Bu \in H^2(Q)$. (Reflection extension) (Ok in 1D)

Remark 5.42 If $u \in H^2(Q_+)$, then $\nabla u \in H^1(Q_+)$, so $\nabla u|_{\partial Q_+}$ by trace theory. In general: $\Omega \subseteq \mathbb{R}^d$, C^2 -boundary condition, then the same result holds.

Remark 5.43 In 1D: $\begin{cases} u \in H^2(0, 1) \\ u(0) = 0 \\ u'(0) = 0 \end{cases}$, $u|_{Q_0} \in L^2(Q_0)$, 1D: $Q_0 = \{0\}$. In general:

If $u \in H^1(0, 1)$, then $u(0)$ is determined by trace theory. If $u \in H^2(0, 1)$, $u'(0)$ is determined. Sobolev:

$$\begin{aligned} H^1(0, 1) &\subseteq C([0, 1]) \\ H^2(0, 1) &\subseteq C^1([0, 1]) \end{aligned}$$

Lemma 5.44 (Poincare inequality) Let Ω be open, bounded connected with C^1 -boundary. Then for all $g \in L^2(\partial\Omega)$ s.t. $g \neq \text{constant}$ there is a $C > 0$ s.t.

$$\|u\|_{L^2(\Omega)} \leq C \|\nabla u\|_{L^2(\Omega)}$$

for all $u \in M$, where

$$M = \{v \in H^1(\Omega) \mid v|_{\partial\Omega} = g\}.$$

Proof. We assume that the statement does not hold true. Then there is a sequence $\{u_n\} \subseteq H^1(\Omega)$, $u_n|_{\partial\Omega} = g$ s.t.

$$\|\nabla u_n\|_{L^2(\Omega)} \rightarrow 0, \quad \|u_n\|_{L^2(\Omega)} = 1.$$

Since $\{u_n\}$ is bounded in $H^1(\Omega)$, by the Banach-Alaoglu theorem (5.30), up to a subsequence

$$u_n \rightarrow u_0 \quad \text{weakly in } H^1(\Omega)$$

Since $\nabla u_n \rightarrow 0$ strongly in L^2 and $\nabla u_n \rightarrow \nabla u_0$ weakly in L^2 , we have $\nabla u_0 = 0$, so $u_0|_{\partial\Omega} = \text{const.}$ (here we need Ω to be connected), so $u_0|_{\partial\Omega} = \text{const.}$ On the other hand, note that M is convex and closed in $H^1(\Omega)$ since the trace operator $T : H^1(\Omega) \rightarrow L^2(\partial\Omega)$ is continuous. Therefore, M is also weakly closed in $H^1(\Omega)$ by the Hahn-Banach theorem. Thus from $\{u_n\} \subseteq M$, $u_n \rightarrow u_0$ weakly in $H^1(\Omega)$ we get that $u_0 \in M$, so $u_0|_{\partial\Omega} = g$. We get a contradiction since $g \neq \text{const}$ ■

Theorem 5.45 (Solution for Poisson Equation with inhomogeneous boundary condition) Let Ω be open, bounded with C^1 -boundary. Let $f \in L^2(\Omega)$, $g \in L^2(\partial\Omega)$. There there is a unique $u \in H^1(\Omega)$ s.t.

$$\begin{cases} -\Delta u = f & \text{in } D'(\Omega) \\ u|_{\partial\Omega} = g & \text{on } \partial\Omega \end{cases}$$

Here $u|_{\partial\Omega} = T(u) \in L^2(\partial\Omega)$ is defined by the trace operator. Moreover if Ω is connected and $g \neq \text{constant}$, then u is the unique minimizer for the variational problem

$$E = \inf_{v \in M} \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v,$$

where $M = \{v \in H^1(\Omega), v|_{\partial\Omega} = g \text{ on } \partial\Omega\}$

Proof. First let us assume that Ω is connected and $g \neq \text{const.}$

Step 1: We prove that $E = \inf_{v \in M} E(v)$ has a minimizer. By Poincaré's Inequality (5.44), for all $v \in M$:

$$\begin{aligned} E(v) &= \frac{1}{2} \int_{\Omega} |\nabla v|^2 - \int_{\Omega} f v \\ (\text{Hölder}) &\geq \frac{1}{2} \|\nabla v\|_{L^2(\Omega)}^2 - \|f\|_{L^2(\Omega)} \|v\|_{L^2(\Omega)} \\ (\text{Poincaré 5.44}) &\geq \frac{1}{2} \|\nabla v\|_{L^2(\Omega)}^2 - C \|f\|_{L^2(\Omega)} \|\nabla v\|_{L^2(\Omega)} \\ &\geq \frac{1}{4} \|\nabla v\|_{L^2(\Omega)}^2 - C \|f\|_{L^2(\Omega)} \end{aligned}$$

Thus $E = \inf_{v \in M} E(v) > -\infty$. Moreover, taking a minimizing sequence $\{v_n\} \subseteq M$, $E(v_n) \rightarrow E$, we find that $\|\nabla v_n\|_{L^2(\Omega)}$ is bounded, and hence $\|v_n\|_{H^1(\Omega)}$ is bounded (by Poincaré inequality) again. By Banach-Alaoglu (5.30), up to a subsequence we have $v_n \rightarrow u$ weakly in $H^1(\Omega)$. Hence

$$\begin{cases} \limsup_{n \rightarrow \infty} \int_{\Omega} |\nabla v_n|^2 \geq \int_{\Omega} |\nabla u|^2 & \text{as } \nabla v_n \rightarrow \nabla u \text{ in } L^2 \\ \int_{\Omega} v_n f \rightarrow \int_{\Omega} u f & \text{as } v_n \rightarrow u \text{ in } L^2 \end{cases}$$

Note that $\{v_n\} \subseteq M$, $v_n \rightarrow u$ in $H^1(\Omega)$ and M is weakly closed in $H^1(\Omega)$ (as argued in the proof of Poincaré inequality), therefore $u \in M$. This means that u is a minimizer for $E = \inf_{v \in M} E(v)$.

Step 2: Now we prove that if u is a minimizer for E , then $-\Delta u = f$ in $D'(\Omega)$. In fact, for all $\phi \in C_c^\infty(\Omega)$ we have

$$E(u) \leq E(u + t\phi) \quad \forall t \in \mathbb{R}$$

because $u + t\phi \in M$. So we get that

$$0 = \frac{d}{dt} E(u + t\phi)|_{t=0} = \int_{\Omega} \nabla u \nabla \phi - \int_{\Omega} f \phi$$

Thus

$$\int_{\Omega} u(-\Delta \phi) = \int_{\Omega} \nabla u \nabla \phi = \int_{\Omega} f \phi \quad \forall \phi \in C_c^\infty(\Omega).$$

So $-\Delta u = f$ in $D'(\Omega)$.

Step 3: We prove that Poisson's equation has at most one solution. Assume that u_1, u_2 are 2 solutions. Then $u = u_1 - u_2$ solves

$$\begin{cases} -\Delta u = 0 & \text{in } \Omega \\ u|_{\partial\Omega} = 0 & \text{on } \Omega \end{cases}$$

so $u = 0$.

Step 4: If $g = c_0$ is a constant, then Poisson's equation can be rewritten with $\tilde{u} = u - c_0$:

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u|_{\partial\Omega} = c_0 & \text{on } \Omega \end{cases} \Leftrightarrow \begin{cases} -\Delta \tilde{u} = f & \text{in } \Omega \\ \tilde{u} = 0 & \text{on } \Omega \end{cases}$$

If Ω is not connected, then by considering connected components of Ω we can prove that Poisson's equation always has a unique solution (for all $f \in L^2(\Omega), g \in L^2(\partial\Omega)$).

■

5.6 Final Remarks

We can describe $H_0^1(\Omega)$ as the kernel of the trace operator $T : H^1(\Omega) \rightarrow L^2(\partial\Omega)$

Theorem 5.46 Let $\Omega \subseteq \mathbb{R}^d$ be open, bounded with C^1 -boundary. Then:

$$H_0^1(\Omega) = \{u \in H^1(\Omega) \mid T(u) = 0 \text{ on } \partial\Omega\}$$

Recall that if $u \in H^1(\Omega) \cap C(\bar{\Omega})$, then $T(u) = u|_{\partial\Omega}$ is the usual restriction. In this case we recover a result proved before.

Proof.

■

Recall that the variational characterization of the Poisson equation

$$\begin{cases} -\Delta u = f & \text{in } \Omega \\ u = g & \text{on } \partial\Omega \end{cases}$$

is

$$\int_{\Omega} \nabla u \nabla \phi = \int_{\Omega} f \phi \quad \forall \phi \in M$$

where $M = \{v \in H^1(\Omega) \mid v = g \text{ on } \partial\Omega\}$. In fact, if $u \in H^2(\Omega)$ and

$$\int_{\Omega} \nabla u \nabla \phi = \int_{\Omega} f \phi \quad \forall \phi \in H^1(\Omega)$$

Then u satisfies the Neumann condition:

$$\frac{\partial u}{\partial n} = \nabla u \cdot \vec{n} = 0 \text{ on } \partial\Omega$$

(justification ...)

For the exercises of sheet 10: Let $\Omega = (a, b) \subseteq \mathbb{R}$ be an open bounded interval. For every $u \in H^1(\Omega)$ the values $u(a)$ and $u(b)$ are determined uniquely by trace theory, or by Sobolev's embedding theorem. Recall: If $u \in H^1((a, b)) \rightsquigarrow \partial\Omega = \{a, b\}$ counting measure iff $g \in L^2(\partial\Omega)$ i.e. $g(a) = g(b)$ are *well-defined*.

Exercise 5.47 (E 10.1) a) Prove $H^1(\mathbb{R}) \subseteq (C(\mathbb{R}) \cap L^\infty(\mathbb{R}))$

Hint: You can use Fourier Transform

b) $H^1(\Omega) \subseteq C(\Omega)$

Solution. a) Let $u \in H^1(\mathbb{R})$. Then $u, u' \in L^2(\mathbb{R}) \Leftrightarrow \hat{u}(k)(1 + |2\pi k|) \in L^2(\mathbb{R})$.
Thus:

$$u(x) = \int_{\mathbb{R}} \hat{u}(k) e^{2\pi i k x} dk \in C(\mathbb{R}) \cap L^\infty(\mathbb{R})$$

if $\hat{u} \in L^1(\mathbb{R})$. So we have to show $\hat{u} \in L^1(\mathbb{R})$.

$$\begin{aligned} \int_{\mathbb{R}} |\hat{u}(k)| dk &= \int_{\mathbb{R}} \frac{|g(k)|}{1 + |2\pi k|} dk \\ &\leq \left(\int_{\mathbb{R}} |g(k)|^2 dk \right) \left[\int_{\mathbb{R}} \left(\frac{1}{1 + |2\pi k|} \right)^2 dk \right]^{\frac{1}{2}} < \infty \end{aligned}$$

b) Given $u \in H^1(\Omega)$, then there is an extension $\tilde{u} \in H^1(\mathbb{R})$. By a) $\tilde{u} \in C(\mathbb{R})$, so $u = \tilde{u}|_{\bar{\Omega}} \in C(\bar{\Omega})$. Remark: We have $\|u\|_{L^\infty(\Omega)} \leq C\|u\|_{H^1(\Omega)}$, where $\Omega = (a, b)$ or \mathbb{R} (but only in 1D) ■

Recall: If $\Omega \subseteq \mathbb{R}^d (d \geq 1)$ open, bounded with C^1 -boundary. Then

$$\|u\|_{L^2(\Omega)} \leq C \|\nabla u\|_{L^2(\Omega)} \quad \forall u \in H_0^1(\Omega)$$

Actually the same bound holds if $u \in H^1(\Omega)$ and $u|_\Gamma = 0$ for an open subset $\Gamma \subseteq \partial\Omega$. In 1D we have:

Exercise 5.48 (E 10.2 (Poincare inequality)) Let $u \in H^1(\Omega)$, $u(a) = 0$. Prove that there exists a constant $C > 0$ such that

$$\|u\|_{L^2(\Omega)} \leq C \|u'\|_{L^2(\Omega)}$$

Solution. Let $u \in C^1(\bar{\Omega})$ and $u(a) = 0$. Then:

$$\begin{aligned} u(x) &= u(a) + \int_a^x u'(t) dt \quad \forall x \in (a, b) \\ \Rightarrow |u(x)| &\leq \int_a^x |u'(t)| dt \leq \int_a^b |u'(t)| dt = \|u'\|_{L^1(\Omega)} \leq C \|u'\|_{L^2(\Omega)} \end{aligned}$$

as Ω is bounded. This implies:

$$\frac{1}{C} \|u\|_{L^2(\Omega)} \leq \|u\|_{L^\infty(\Omega)} \leq C \|u'\|_{L^2(\Omega)}$$

To extend this for $u \in H^1(\Omega)$, we can use a density argument. More precisely, for all $u \in H^1(\Omega)$ there is a sequence $\{u_n\} \subseteq C^1(\bar{\Omega})$ s.t $u_n \rightarrow u$ in $H^1(\Omega)$. Then:

$$\|u\|_{L^2(\Omega)} = \lim_{n \rightarrow \infty} \|u_n\|_{L^2(\Omega)} \leq C \lim_{n \rightarrow \infty} \|u'_n\|_{L^2(\Omega)} = C \|u'\|_{L^2(\Omega)}$$

Recall: For all $f \in W_{loc}^{1,1}(O)$ with O in \mathbb{R}^d we have

$$f(x) - f(y) = \int_0^1 \nabla f(y + t(x - y))(x - y) dt$$

if $x, y \in O$, $y + t(x - y) \in O$ for all $t \in [0, 1]$. For 1D: If $u \in H^1(a, b)$:

$$u(x) - u(y) = \int_y^x u'(t) dt \quad \forall x, y \in (a, b) \quad \blacksquare$$

Exercise 5.49 (E 10.3 (Poincare inequality)) Let $u \in H^2(\Omega)$ and $f \in L^2(\Omega)$. Prove that the following statements are equivalent:

a) u solves the equation:

$$\begin{cases} -u'' = f & \text{in } D'(\Omega) \\ u'(0) = u'(1) = 0 \end{cases}$$

b)

$$\int_{\Omega} u' \phi' = \int_{\Omega} f \phi$$

for all $\phi \in H^1(\Omega)$.

Here $u \in H^2(\Omega) \Rightarrow u' \in H^1(\Omega) \Rightarrow u'(0), u'(1)$ determined uniquely by trace theorem / Sobolev inequality $H^1(\Omega) \subseteq C(\bar{\Omega})$

Solution.

b) \Rightarrow a) For all $\phi \in C_c^\infty(\Omega)$:

$$\int_{\Omega} f \phi = \int_{\Omega} u' \phi' = - \int_{\Omega} u \phi''$$

This implies $-u'' = f$ in $D'(\Omega)$ a.e. Thus for all $\phi \in H^1(\Omega)$:

$$\int_{\Omega} f \phi = \int_{\Omega} -u'' \phi = \int_{\Omega} u' \phi' - [u' \phi]_a^b$$

By b) we conclude $0 = [u' \phi]_a^b = u'(b)\phi(b) - u'(a)\phi(a)$ for all $\phi \in H^1(\Omega)$. We can choose $\phi \in H^1(\Omega)$ s.t. $\phi(a) = 0, \phi(b) = 1$. This implies $\phi'(b) = 0$. Similarly, we can choose $\phi \in H^1(\Omega)$ s.t. $\phi(a) = 1, \phi(b) = 0$. This implies $u'(a) = 0$.

a) \Rightarrow b) From a) and Integration by parts:

$$\int_{\Omega} f \phi = \int_{\Omega} -u'' \phi = \int_{\Omega} u' \phi' - \underbrace{[u' \phi]_a^b}_{=0 \text{ as } u'(a)=u'(b)=0}$$

This implies:

$$\int_{\Omega} f \phi = \int_{\Omega} u' \phi' \quad \forall \phi \in H^1(\Omega)$$

■

Exercise 5.50 (E 10.4 (Robin boundary condition)) Let $f \in L^2(\Omega)$.

a) Prove that there exists a unique $u \in M := \{\phi \in H^1(\Omega), u(a) = 0\}$ s.t.

$$\int_{\Omega} u' \phi' = \int_{\Omega} f \phi \quad \forall \phi \in M$$

b) Prove that the above function u is the unique solution to the equation

$$\begin{cases} -u'' = f & \text{in } D'(\Omega) \\ u(a) = 0 & u'(b) = 0 \end{cases}$$

Solution. a) By 10.2 we have

$$\|\phi\|_{L^2(\Omega)} \leq C \|\phi'\|_{L^2(\Omega)} \quad \forall \phi \in M$$

Thus: $(M, \|\phi\|_M := \|\phi'\|_{L^2(\Omega)})$ is a Hilbert space. More precisely, we know $(M, \|\cdot\|_M)$ is a closed subspace of $H^1 \rightsquigarrow$ a Hilbert space. And $\|\cdot\|_M$ is comparable to $\|\cdot\|_{H^1}$. By Riesz representation theorem there is a unique $u \in M$ s.t. $\langle \phi, u \rangle_M = F(\phi)$ for all $\phi \in M$. We use this for

$$F(\phi) = \int_{\Omega} f \phi \quad \forall \phi \in M$$

Here $|F(\phi)| \leq \|f\|_{L^2} \|\phi\|_{L^2}$.

b) Let $u \in M$ be the solution in (a) i.e.

$$\int_{\Omega} f \phi = \int_{\Omega} u' \phi' \quad \forall \phi \in M$$

Then we prove that u solves

$$\begin{cases} -u'' = f & \text{in } D'(\Omega) \\ u(a) = u'(b) = 0 \end{cases}$$

Since $u \in M$ we have $u \in H^1(\Omega)$ and $u(a) = 0$. From

$$\int_{\Omega} f \phi = \int_{\Omega} u' \phi' \quad \forall \phi \in M$$

we get for all $\phi \in C_c^\infty(\Omega)$:

$$\int_{\Omega} f \phi = \int_{\Omega} u' \phi' = \int_{\Omega} -u \phi''$$

So we get $-u'' = f$ in $D'(\Omega)$. Since $f \in L^2(\Omega) \Rightarrow u'' \in L^2(\Omega) \Rightarrow u \in H^2(\Omega) \Rightarrow u' \in H^1(\Omega) \Rightarrow u'(b)$ is uniquely determined. For all $\phi \in M$:

$$\int_{\Omega} f \phi = \int_{\Omega} -u'' \phi = \int_{\Omega} u' \phi' - (u'(b)\phi(b) - u'(a)\phi(a)) \quad \text{as } \phi \in M$$

and $\int_{\Omega} f \phi = \int_{\Omega} u' \phi'$. This implies:

$$u'(b)\phi(b) = 0 \quad \forall \phi \in M$$

Take $\phi(x) = \frac{x-a}{b-a} \in M$, $\phi(b) = 1$. Uniqueness of the solution: Take u s.t.

$$\begin{cases} -u'' = f & \text{in } D'(\Omega) \\ u(a) = u'(b) = 0 \end{cases}$$

This implies $u \in H^2(\Omega)$. By integration by parts: For all $\phi \in H^1(\Omega)$, $\phi(a) = 0$.

$$\int_{\Omega} f \phi = \int_{\Omega} -u'' \phi = \int_{\Omega} u' \phi' \quad \forall \phi \in M$$

Thus $u \in M$ and

$$\int_{\Omega} f \phi = \int_{\Omega} u' \phi' \quad \forall \phi \in M. \quad \blacksquare$$

Exercise 5.51 (Bonus 9) Prove that the solution u in Problem E 10.4 is the unique minimizer for the minimization problem:

$$E = \inf_{v \in M} \left(\int_{\Omega} |v'|^2 - \int_{\Omega} f v \right)$$

Chapter 6

Heat Equation

6.1 Fundamental Solution

$$\begin{cases} \partial_t u = \Delta u & (x, t) \in \mathbb{R}^d \times (0, \infty) \\ u = g & (x, t) \in \mathbb{R}^d \times \{0\} \end{cases}$$

The fundamental solution is:

$$\Phi(x, t) = \frac{1}{(4\pi t)^{\frac{d}{2}}} e^{-\frac{|x|^2}{4t}}, \quad x \in \mathbb{R}^d, t > 0$$

We have:

$$\begin{cases} \partial_t \Phi = \Delta \Phi & (x, t) \in \mathbb{R}^d \times (0, \infty) \\ \int_{\mathbb{R}^d} \Phi(x, t) dx = 1 & \forall t > 0 \\ \lim_{t \rightarrow 0} \Phi(x, t) = \delta_0(x) & \text{in } D'(\mathbb{R}^d) \end{cases}$$

Theorem 6.1 If $g \in C(\mathbb{R}^d) \cap L^\infty(\mathbb{R}^d)$, then

$$u(x, t) := \int_{\mathbb{R}^d} \Phi(x - y, t) g(y) dy$$

satisfies

- (i) $u \in C^\infty(\mathbb{R}^d \times (0, \infty))$
- (ii) $\partial_t u = \Delta u$ for all $(x, t) \in \mathbb{R}^d \times (0, \infty)$
- (iii) $\lim_{t \rightarrow 0} u(x, t) = g(x)$ for all $x \in \mathbb{R}^d$

Notation 6.2 For functions of (x, t) we introduce the following notation for different regularity in x and t .

$$f \in C_1^2 \Leftrightarrow f, D_x f, D_x^2 f, \partial_t f \in C$$

Theorem 6.3 (Nonhomogeneous problem) Let $f \in C_1^2(\mathbb{R}^d, [0, \infty))$ be compactly supported. Define

$$u(x, t) = \int_0^t \int_{\mathbb{R}^d} \Phi(x - y, t - s) f(y, s) dy ds$$

Then

- (i) $u \in C_1^2(\mathbb{R}^d \times (0, \infty))$
- (ii) $\partial_t u = \Delta u + f$ for all $x \in \mathbb{R}^d, t > 0$
- (iii) $\lim_{t \rightarrow 0} u(x, t) = 0$ for all $x \in \mathbb{R}^d$.

Proof. We write

$$u(x, t) = \int_0^t \int_{\mathbb{R}^d} \Phi(y, s) f(x - y, t - s) dy ds$$

With the Leibniz integral rule we get

$$\partial_t u(x, t) = \int_0^t \int_{\mathbb{R}^d} \Phi(y, s) \partial_t f(x - y, t - s) dy ds + \int_{\mathbb{R}^d} \Phi(y, s) f(x - y, 0) dy$$

and

$$\partial_{ij} u(x, t) = \int_0^t \int_{\mathbb{R}^d} \Phi(y, s) \partial_{ij} f(x - y, t - s) dy.$$

This shows that $\partial_t u, \partial_{ij} u$ are in $C(\mathbb{R}^d \times (0, \infty))$. Next we calculate:

$$\begin{aligned} \partial_t u - \Delta u &= \int_0^t \int_{\mathbb{R}^d} \Phi(y, s) (\partial_t - \Delta_x) f(x - y, t - s) dy ds + \int_{\mathbb{R}^d} \Phi(y, s) f(x - y, 0) dy \\ &= \underbrace{\int_\epsilon^t \int_{\mathbb{R}^d} \Phi(y, s) (\partial_t - \Delta_x) f(x - y, t - s) dy ds}_{=: I_\epsilon} \\ &\quad + \underbrace{\int_0^\epsilon \int_{\mathbb{R}^d} \Phi(y, s) (\partial_t - \Delta_x) f(x - y, t - s) dy ds}_{J_\epsilon} \\ &\quad + \underbrace{\int_{\mathbb{R}^d} \Phi(y, s) f(x - y, 0) dy}_K \end{aligned}$$

Then

$$\begin{aligned} |J_\epsilon| &\leq \|(\partial_t - \Delta_x) f\|_{L^\infty} \int_0^\epsilon \int_{\mathbb{R}^d} \Phi(y, s) dy ds \leq C\epsilon \xrightarrow{\epsilon \rightarrow 0} 0 \\ I_\epsilon &= \int_\epsilon^t \int_{\mathbb{R}^d} \Phi(y, s) (-\partial_s - \Delta_y) f(x - y, t - s) dy ds \\ \text{(Green (2.3))} \quad &= \int_\epsilon^t \int_{\mathbb{R}^d} \underbrace{(\partial_s - \Delta_y) \Phi(y, s)}_{=0} f(x - y, t - s) dy ds \\ &\quad - \left[\int_{\mathbb{R}^d} \Phi(y, s) f(x - y, t - s) dy \right]_{s=\epsilon}^{s=t} \end{aligned}$$

This implies:

$$\begin{aligned} I_\epsilon + K &= \int_{\mathbb{R}^d} \Phi(y, \epsilon) f(x - y, t - \epsilon) dy \\ &\xrightarrow{\epsilon \rightarrow 0} \int_{\mathbb{R}^d} \delta_0(y) f(x - y, t) dy = f(x, t) \end{aligned}$$

Thus

$$\partial_t u - \Delta u = f(x, t) \quad \forall (x, t) \in \mathbb{R}^d \times (0, \infty)$$

Finally:

$$\|u(\cdot, t)\|_{L^\infty} \leq \|f\|_{L^\infty} \int_0^t \int_{\mathbb{R}^d} \Phi(y, s) dy ds = \|f\|_{L^\infty} t \xrightarrow{t \rightarrow 0} 0$$

■

Exercise 6.4 If f, g are given as above, then

$$u(x, t) = \int_{\mathbb{R}^d} \Phi(x - y, t) g(y) dy + \int_0^t \int_{\mathbb{R}^d} \Phi(x - y, t - s) f(y, s) ds$$

solves

$$\begin{cases} \partial_t u - \Delta u = f \\ u(\cdot, 0) = g \end{cases}$$

Remark 6.5 (Duhamel formula) Consider the ODE $\partial_t w(t) = Aw(t)$ for all $A \in \mathbb{R}$. Then the solution is

$$w(t) = e^{tA} w(0).$$

More generally: If $\partial_t w(t) = Aw(t) + f(t)$, then

$$\begin{aligned} \partial_t(e^{-tA} w(t)) &= e^{-tA} (\partial_t w(t) - Aw(t)) = e^{-tA} f(t) = e^{-tA} f(t) \\ \Rightarrow e^{-tA} w(t) &= w(0) + \int_0^t e^{-sA} f(s) ds \\ \Rightarrow w(t) &= e^{tA} w(0) + \int_0^t e^{(t-s)A} f(s) ds \end{aligned}$$

More generally, if A is an operator (independent of time) then:

$$\begin{aligned} \partial_t w(t) &= Aw(t) + f(t) \\ \Rightarrow w(t) &= e^{tA} w(0) + \int_0^t e^{(t-s)A} f(s) ds \end{aligned}$$

Application: If $A = \Delta$, then the operator $e^{t\Delta}$ has kernel

$$e^{t\Delta}(x, y) = \Phi(x - y, t) = \frac{1}{(4\pi t)^{\frac{d}{2}}} e^{-\frac{|x-y|^2}{4t}}.$$

This is called the *heat kernel*.

Theorem 6.6 (L^2 -data) For every $g \in L^2(\mathbb{R}^d)$, define

$$u(t, x) = \int_{\mathbb{R}^d} \Phi(x - y, t) g(y) dy$$

Then $u \in C^\infty(\mathbb{R}^d \times (0, \infty))$ and it solves the heat equation

$$\begin{cases} \partial_t u = \Delta_x u & \mathbb{R}^d \times (0, \infty) \\ \lim_{t \rightarrow 0} u(\cdot, t) = g & \text{in } L^2(\mathbb{R}^d) \end{cases}$$

Proof. Recall the heuristic computation from the heat equation using the Fourier transform

$$\begin{aligned}
& \partial_t u(x, t) = \Delta_x u(x, t) \\
\Leftrightarrow & \partial_t \hat{u}(k, t) = -|2\pi k|^2 \hat{u}(k, t) \\
\Leftrightarrow & \partial_t (e^{t|2\pi k|^2} \hat{u}(k, t)) = 0 \\
\Leftrightarrow & e^{t|2\pi k|^2} \hat{u}(k, t) = \hat{u}(k, 0) = \hat{g}(k) \\
\Leftrightarrow & \hat{u}(k, t) = e^{-t|2\pi k|^2} \hat{g}(k) = \hat{\Phi}(k, t) \hat{g}(k) = \widehat{\Phi \star g} \quad \blacksquare \\
\Leftrightarrow & u(x, t) = \Phi \star g = \int_{\mathbb{R}^d} \Phi(x - y, t) g(y) dy
\end{aligned}$$

Here we only need the direction \Leftarrow which is rigorous if $g \in L^2(\mathbb{R}^d)$. From the Fourier transform, it is also easy to check that $u(\cdot, t) \rightarrow g$ in L^2 as $t \rightarrow 0$ (exercise). To see the smoothness, note that for all $t > 0$, and for all $m \in \mathbb{N}$:

$$(1 + |2\pi k|^m) \hat{u}(k, t) = \underbrace{(1 + |2\pi k|^m) e^{-t|2\pi k|^2}}_{\in L^\infty} \underbrace{\hat{g}(k)}_{\in L^2} \in L^2$$

This implies $u(\cdot, t) \in H^m(\mathbb{R}^d)$ for all $m \geq 1$, so $u(\cdot, t) \in C^\infty(\mathbb{R}^d)$ by Sobolev embedding (see below). This argument can also be used to show that $u \in C^\infty(\mathbb{R}^d \times (0, \infty))$ (exercise)

Theorem 6.7 (Sobolev embedding) If $m > \frac{d}{2}$, then $H^m(\mathbb{R}^d) \subseteq (C(\mathbb{R}^d) \cap L^\infty(\mathbb{R}^d))$.

Proof. We write for all $u \in H^m(\mathbb{R}^d)$:

$$\hat{u}(k) = \underbrace{\hat{u}(k)(1 + |2\pi k|^m)}_{\in L^2 \text{ as } u \in H^m} \underbrace{\frac{1}{1 + |2\pi k|^m}}_{\in L^2 \text{ as } m > \frac{d}{2}}$$

This implies $\hat{u}(k) \in L^1(\mathbb{R}^d)$ and finally $u = (\hat{u})^\vee \in (C(\mathbb{R}^d) \cap L^\infty(\mathbb{R}^d))$. ■

Exercise 6.8 (E 11.1) Let $g \in L^2(\mathbb{R}^d)$,

$$u(x, t) = \int_{\mathbb{R}^d} \Phi(x - y, t) g(y) dy, \quad \Phi(x, t) = \frac{1}{(4\pi t)^{\frac{d}{2}}} e^{-\frac{|x|^2}{4t}}$$

be the fundamental solution of the heat equation

$$\begin{cases} \partial_t u - \Delta_x u = 0 & \forall (x, t) \in \mathbb{R}^d \times (0, \infty) \\ u(x, t) \rightarrow g(x) & \text{as } t \rightarrow 0. \end{cases}$$

Prove that

- a) $u \in C^\infty(\mathbb{R}^d \times (0, \infty))$.
- b) $\|u(\cdot, t) - g\|_{L^2(\mathbb{R}^d)} \xrightarrow{t \rightarrow 0^+} 0$
- c) If $g \in H^1(\mathbb{R}^d)$, then $\|u(\cdot, t) - g\|_{L^2(\mathbb{R}^d)} \leq C\sqrt{t}$ as $t \rightarrow 0^+$.

Solution. a) We prove for all $t > 0$:

$$u(x, t) \in \bigcap_{m \geq 1} H^m(\mathbb{R}^d) \subseteq C^\infty(\mathbb{R}^d)$$

We use the Fourier transform:

$$\hat{\Phi}(k, t) = e^{-t|2\pi k|^2}$$

Recall $\widehat{e^{-\pi|x|^2}} = e^{-\pi|k|^2}$. From this we get $\widehat{e^{-\pi\lambda|x|^2}} = \lambda^{-\frac{d}{2}} e^{-\frac{\pi|k|^2}{\lambda}}$. Then:

$$\widehat{e^{-\frac{|x|^2}{4t}}} = e^{-\pi\frac{1}{4\pi t}|x|^2} = \left(\frac{1}{4\pi t}\right)^{-\frac{d}{2}} e^{-\pi|k|^2 4\pi t} = (4\pi t)^{\frac{d}{2}} e^{-t|2\pi k|^2}$$

Hence:

$$\hat{u}(k, t) = \hat{\Phi}(k, t)\hat{g}(k) = e^{-t|2\pi k|^2}\hat{g}(k) \in L^1(\mathbb{R}^d, dk) \quad \forall t > 0$$

This implies:

$$u(x, t) = \int_{\mathbb{R}^d} e^{-t|2\pi k|^2} \hat{g}(k) e^{2\pi i k x} dk \quad \forall (x, t) \in \mathbb{R}^d \times (0, \infty)$$

Consequently:

$$D_x^\alpha u(x, t) = \int_{\mathbb{R}^d} \underbrace{e^{-t|2\pi k|^2} \hat{g}(k) (2\pi i k)^\alpha}_{L^1(\mathbb{R}^d, dk)} e^{2\pi i k x} dk \in C(\mathbb{R}^d, (0, \infty))$$

$$D_t^\alpha u(x, t) = \int_{\mathbb{R}^d} (-|2\pi k|^2)^\alpha e^{-t|2\pi k|^2} \hat{g}(k) e^{2\pi i k x} dk \in C(\mathbb{R}^d, (0, \infty))$$

Also:

$$\begin{aligned} & \partial_t u - \Delta_x u \\ &= \int_{\mathbb{R}^d} -|2\pi k|^2 e^{-t|2\pi k|^2} \hat{g}(k) e^{2\pi i k x} dk + \int_{\mathbb{R}^d} e^{-t|2\pi k|^2} \hat{g}(k) |2\pi i k|^2 e^{2\pi i k x} dk \\ &= 0 \end{aligned}$$

b) Finally:

$$\begin{aligned} \int_{\mathbb{R}^d} |u(x, t) - g(x)|^2 dx &= \int_{\mathbb{R}^d} |\hat{u}(k, t) - \hat{g}(k)|^2 dk \\ &= \int_{\mathbb{R}^d} \underbrace{|e^{-t|2\pi k|^2} - 1|^2}_{\in [0, 1]} \underbrace{|\hat{g}(k)|^2}_{\in L^1(\mathbb{R}^d)} dk \xrightarrow{t \rightarrow 0} 0 \end{aligned}$$

by dominated convergence. Now,

$$\begin{aligned} \int_{\mathbb{R}^d} |u(x, t)|^2 dx &= \int_{\mathbb{R}^d} |\hat{u}(k, t)|^2 dk \\ &= \int_{\mathbb{R}^d} \underbrace{e^{-2t|2\pi k|^2}}_{\in [0, 1] \text{ and } \xrightarrow{t \rightarrow 0} 0} |\hat{g}(k)|^2 dk \xrightarrow{t \rightarrow \infty} 0 \end{aligned}$$

c) Assume $g \in H^1(\mathbb{R}^d) \Leftrightarrow \int_{\mathbb{R}^d} (1 + |2\pi k|^2) |\hat{g}(k)|^2 dk < \infty$. We claim for all $s \geq 0$ that $|1 - e^{-s}| \leq \min(1, Cs) \leq C\sqrt{s}$: We have that $s \mapsto \left| \frac{1 - e^{-s}}{s} \right|$ is bounded and continuous in $[0, 1]$ as $\left| \frac{1 - e^{-s}}{s} \right| \rightarrow 1$, so $\frac{1 - e^{-s}}{s} \leq C$ for all $s \in [0, 1]$.

$$\begin{aligned} \int_{\mathbb{R}^d} |u(x, t) - g(x)|^2 dx &= \int_{\mathbb{R}^d} \underbrace{\left| 1 - e^{-t|2\pi k|^2} \right|^2}_{\leq C(t|2\pi k|^2)} |\hat{g}(k)|^2 dk \\ &\leq C \int_{\mathbb{R}^d} t|2\pi k|^2 |\hat{g}(k)|^2 dk \\ &\leq Ct \|g\|_{H^1}^2 \quad \forall t > 0 \end{aligned}$$

■

Step 1: Spectral problem:

$$\begin{cases} -\Delta u_n = \lambda_n u_n & \text{in } \Omega \\ u_n|_{\partial\Omega} = 0 \end{cases}$$

Lemma 6.9 There is a $\lambda_n > 0$, $\lambda_n \xrightarrow{n \rightarrow \infty} \infty$ and an orthonormal family $\{u_n\} \subseteq L^2(\Omega)$ s.t. $u_n \in H_0^1(\Omega) \cap C^\infty(\Omega)$ solving this eigenvalue equation.

Step 2:

$$\begin{cases} \partial_t - \Delta_x u = 0 \\ u(x, 0) = g(x) \end{cases} \Rightarrow \begin{cases} \partial_t \langle u_n, u \rangle_{L^2(\Omega)} = \langle u_n, \Delta_x u \rangle = \langle \Delta_x u_n, u \rangle = -\lambda_n \langle u_n, u \rangle \\ \langle u_n, u \rangle_{t=0} = \langle u_n, g \rangle \end{cases}$$

$$\Rightarrow \langle u_n, u \rangle = e^{-t\lambda_n} \langle u_n, g \rangle \quad \forall t > 0, \forall n = 1, 2, \dots$$

$$\Rightarrow u = \sum_{n=0}^{\infty} \langle \cdot \rangle = - \sum e^{-t\lambda_n} \langle \cdot \rangle u$$

Example 6.10 $\Omega = (0, 1)$,

$$\begin{cases} -u_n'' = \lambda_n u_n & \text{in } (0, 1) \\ u(0) = u(1) = 0 \end{cases}$$

has solution

$$\begin{cases} u_n(x) = \sqrt{2} \sin(\pi n x) & n = 1, 2, \dots \\ \lambda_n = (\pi n)^2 \end{cases}$$

has a solution:

$$u(x, t) = \sum_{n=1}^{\infty} e^{-t\lambda_n} \underbrace{\langle u_n, g \rangle}_{g_n} u_n(x) = \sum_{n=1}^{\infty} e^{-t\pi^2 n^2} g_n \sin(\pi n x),$$

$$\int_0^1 \sin(n\pi x)^2 dx = \frac{1}{2} \quad \forall n > 1$$

$$g_n = \sqrt{2} \langle u_n, g \rangle = 2 \int_0^1 \sin(\pi n x) g(x) dx$$

Exercise 6.11 (E 11.2) Consider the heat equation in a bounded domain

$$\begin{cases} \partial_t u(x, t) = \Delta_x u(x, t) & \forall x \in \Omega, t > 0 \\ u(x, t) = 0 & \forall x \in \partial\Omega, t > 0 \\ u(x, 0) = g(x) & \forall x \in \Omega \end{cases}$$

Let us focus on the simplest case $\Omega = (0, 1)$. Prove that for every $g \in C_c^1(0, 1)$, the function

$$u(x, t) = \sum_{n=1}^{\infty} g_n e^{-t\pi^2 n^2} \sin(n\pi x), \quad g_n = 2 \int_0^1 g(y) \sin(n\pi y) dy$$

is a classical solution to the above heat equation.

Solution. Direct proof of heat equation. $g \in C_c^1(0, 1) \subseteq H_0^1(0, 1)$, $\Rightarrow \sum_n \pi^2 n^2 |g_n|^2 = c \|g'\|_{L^2(0,1)}^2 < \infty$, so $\sum_n |g_n| < \infty$.

$$u(x, 0) = \underbrace{\sum_{n=1}^{\infty} g_n \sin(\pi n x)}_{\in C[0,1]} = g(x) \quad \forall x \in [0, 1]$$

From $u(x, t) = \sum_{n=1}^{\infty} e^{-t\pi^2 n^2} g_n \sin(\pi n x)$ we get

$$\begin{cases} \partial_t u(x, t) = \sum_{n=1}^{\infty} (-n^2 \pi^2) e^{-t\pi^2 n^2} g_n \sin(\pi n x) & \forall t > 0, \forall x \in (0, 1) \\ \Delta_x u(x, t) = \sum_{n=1}^{\infty} e^{-t\pi^2 n^2} g_n [-(\pi n)^2] \sin(\pi n x) & \forall t > 0, \forall x \in (0, 1) \end{cases}$$

So $\partial_t u - \Delta_x u = 0$ for all $t > 0, x \in (0, 1)$ ■

Exercise 6.12 (E 11.3) Let $g(t) = e^{-\frac{1}{t^2}}$ and denote $g^{(n)}(t)$ the n -th derivative of g . Define

$$u(x, t) = \sum_{n=0}^{\infty} \frac{g^{(n)}(t)}{(2n)!} x^{2n}, \quad \forall x \in \mathbb{R}, t > 0$$

Prove that u is a classical solution to the heat equation

$$\begin{cases} \partial_t u(x, t) = \Delta_x u(x, t) & \forall x \in \mathbb{R}, t > 0 \\ \lim_{t \rightarrow 0} u(x, t) = 0 & \forall x \in \mathbb{R} \end{cases}$$

Solution. Formally:

$$\begin{cases} \partial_t u = \sum_{n=0}^{\infty} \frac{g^{(n+1)}(t)}{(2n)!} x^{2n} \\ -\Delta_x u = \sum_{n=1}^{\infty} \frac{g^{(n)}(t)}{(2n)!} (2n)(2n-1) x^{2n-2} = \sum_{n=1}^{\infty} \frac{g^{(n)}(t)}{(2n-2)!} x^{2n-2} = \sum_{m=0}^{\infty} \frac{g^{(m+1)}(t)}{(2m)!} x^{2m} \end{cases}$$

This implies $\partial_t u = \Delta_x u$ (if the series are convergent) $(x, t) \in B \times [\epsilon, \frac{1}{\epsilon}]$ for $B \subset \mathbb{R}$ bounded, $\epsilon > 0$. Also

$$\begin{aligned} g(t) &= e^{-\frac{1}{t^2}} \xrightarrow{t \rightarrow 0^+} e^{-\infty} = 0 \\ g'(t) &= e^{-\frac{1}{t^2}} \left(\frac{2}{t^3} \right) \xrightarrow{t \rightarrow 0^+} 0 \\ g''(t) &= e^{-\frac{1}{t^2}} \left(-\frac{3!}{t^4} + \frac{2}{t^3} \right) \xrightarrow{t \rightarrow 0^+} 0 \\ g'''(t) &= e^{-\frac{1}{t^2}} \left(\frac{4!}{t^5} - \frac{3!}{t^4} + \frac{2}{t^3} \right) \end{aligned}$$

Let's prove the convergence of the series:

$$u(x, t) = \sum_{n=0}^{\infty} \frac{g^{(n)}(t)}{(2n)!} x^{2n}$$

converges absolutely for $|x| \leq C, t \in [\epsilon, \frac{1}{\epsilon}], \epsilon > 0$. By induction,

$$g^{(n)}(t) = e^{-\frac{1}{t^2}} \underbrace{\left(\frac{(n+1)!}{t^{n+2}} - \frac{n!}{t^{n+1}} + \frac{(n+1)!}{t^n} - \dots \right)}_{\text{pol in } (\frac{1}{t}), \text{ all cos bounded by } (n+1)} (-1)^{n-1}$$

This implies

$$|g^{(n)}(t)| \leq e^{-\frac{1}{t^2}} [(n+2)!] \left(\frac{1}{t^{n+2}} + 1 \right), \quad \frac{1}{t^s} \leq \left(\frac{1}{t^{n+2}} + 1 \right) \forall s = 0, 1, \dots, n+2$$

Thus

$$\sum_{n \geq 0} \left| \frac{g^{(n)}}{(2n)!} x^{2n} \right| \leq \sum_{n \geq 0} e^{-\frac{1}{t^2}} \frac{(n+2)!}{(2n)!} \left(\frac{1}{t^{n+2}} + 1 \right) x^{2n}$$

(1)

$$\begin{aligned} \sum_{n \geq 0} \frac{(n+2)!}{(2n)!} x^{2n} &= \sum_{n \geq 0} \frac{1}{(n+3)(n+4) \cdots (2n)} \\ &\leq \sum_{n \geq 0} \frac{1}{n^{n-2}} x^{2n} \\ &\leq \sum_{n \geq M} + \sum_{n \geq M} \frac{1}{M^{n-2}} x^{2n} \\ &= M^2 \sum_n \left(\frac{x^2}{M} \right)^n \\ &\leq m^2 \frac{1}{1 - \left(\frac{x^2}{M} \right)} \end{aligned}$$

$$(2) \quad t \in [\epsilon, \frac{1}{\epsilon}], \text{ so } \frac{1}{t} \leq \frac{1}{\epsilon}, \text{ so } \frac{1}{t^{n+2}} \leq \frac{1}{\epsilon^{n+2}} \longrightarrow \sum_{n \geq 0} \frac{(n+2)!}{(2n)!} \frac{1}{t^{n+2}} x^{2n} \leq \sum_{n \geq 0} \frac{1}{n^{n-2}} \frac{1}{\epsilon^{n-2}} x^{2n}$$

■

Remark 6.13 $|u(x, t)| \leq \exp\left(\frac{cx^2}{t}\right) \rightsquigarrow$ unphysical solution. Violates $|u(x, t)| \leq Ce^{C|x|^2}$ for all $\forall(x, t) \in \mathbb{R} \times [0, T]$

Exercise 6.14 (Bonus 10) Consider

$$u(x, t) = \int_{\mathbb{R}^d} \Phi(x - y, t) g(y) dy$$

where $\Phi(x, t) = \frac{1}{(4\pi t)^{\frac{d}{2}}} e^{-\frac{x^2}{4t}}$. Assume $g \in C_c^\infty(\mathbb{R}^d)$. Prove or disprove that

$$\|u(\cdot, t) - g\|_{L^2(\mathbb{R}^d)} \leq C_n t^n$$

as $t \rightarrow 0^+$ for all $n = 1, 2, \dots$

6.2 Maximum Principle

Recall the Poisson equation $-\Delta u \leq 0$ in $\Omega \subseteq \mathbb{R}^d$ open, bounded. Then

$$\sup_{\bar{\Omega}} u(x) = \sup_{\partial\Omega} u(x).$$

Theorem 6.15 (Maximum principle for bounded sets) Let $\Omega \subseteq \mathbb{R}^d$ be open and bounded. Let $T > 0$ and define

$$\begin{aligned} \Omega_T &= \Omega \times (0, T), \\ \partial^* \Omega_T &= (\bar{\Omega} \times \{0\}) \cup (\partial\Omega \times [0, T]) \end{aligned}$$

If $u \in C_1^2(\Omega_T) \cap C(\bar{\Omega}_T)$ solves $\partial_t u - \Delta_x u \leq 0$ in Ω_T , then

$$\max_{\bar{\Omega}_T} u = \max_{\partial^* \Omega_T} u.$$

Proof. We will use Hopf's argument which is simpler than the mean-value theorem (there exists a mean-value theorem for heat equation, but it is complicated and we will not discuss it). Firstly, to illustrate the principle, we prove the maximum principle for the Poisson Equation: Assume $u \in C^2(\Omega) \cap C(\bar{\Omega})$

Step 1) Assume $\Delta u > 0$ in Ω . Since $\bar{\Omega}$ is compact, there is a $x_0 \in \bar{\Omega}$ s.t. $u(x_0) = \max_{x \in \bar{\Omega}} u(x)$. We prove that $x_0 \in \partial\Omega$. In fact, if $x_0 \in \Omega$, then since x_0 is a (local) maximizer of u in Ω , we have $\Delta u(x_0) \leq 0$, which contradicts to the assumption that $\Delta u > 0$ in Ω . Thus $x_0 \in \partial\Omega$, and hence

$$\max_{x \in \bar{\Omega}} u(x) = u(x_0) \leq \max_{x \in \partial\Omega} u(x).$$

Step 2) Now assume $\Delta u \geq 0$ in Ω . Define

$$u_\epsilon(x) = u(x) + \epsilon|x|^2, \quad \epsilon > 0.$$

Then, $\Delta u_\epsilon > 0$ in Ω , hence by Step 1 and

$$u \leq u_\epsilon \leq u + \epsilon \sup_{x \in \bar{\Omega}} |x|^2$$

we have

$$\begin{aligned} \max_{x \in \bar{\Omega}} u(x) &\leq \max_{x \in \bar{\Omega}} u_\epsilon(x) \leq \max_{x \in \partial\Omega} u_\epsilon(x) \\ &\leq \max_{x \in \partial\Omega} u(x) + \epsilon \left(\sup_{x \in \bar{\Omega}} |x|^2 \right) \xrightarrow{\epsilon \rightarrow 0} \max_{x \in \partial\Omega} u(x) \end{aligned}$$

Proof for the heat equation:

Step 1) Assume $u \in C_1^2(\Omega \times (0, T]) \cap C(\bar{\Omega} \times [0, T])$ and

$$\partial_t u - \Delta_x u < 0$$

in $\Omega \times (0, T]$. Then, because of compactness, there is $(x_0, t_0) \in \bar{\Omega} \times [0, T]$ s.t.

$$u(x_0, t_0) = \max_{(x,t) \in \bar{\Omega} \times [0,T]} u(x, t).$$

We prove that $(x_0, t_0) \in \partial^* \Omega_T$. Assume by contradiction that $(x_0, t_0) \notin \partial^* \Omega_T$, then $x_0 \in \Omega$ and $t_0 \in (0, T]$. Since $x \mapsto u(x, t_0)$ has a (local) maximizer $x_0 \in \Omega$ we have that $\Delta_x u(x_0, t_0) \leq 0$. Since $t \mapsto u(x_0, t)$ has a (local) maximizer $t_0 \in (0, T]$ we have that $\partial_t u(x_0, t_0) \geq 0$. This implies:

$$(\partial_t u - \Delta_x u)(x_0, t_0) \geq 0$$

which is a contradiction to the assumption. Thus $(x_0, t_0) \in \partial^* \Omega_T$, i.e. $\max_{\bar{\Omega}_T} u = \max_{\partial^* \Omega_T} u$.

Step 2) Assume $u \in C_1^2(\Omega \times (0, T)) \cap C(\bar{\Omega} \times [0, T])$ and

$$\partial_t u - \Delta_x u \leq 0 \quad \text{in } \Omega \times (0, T).$$

Let $\tilde{T} \in (0, T)$ and for $\epsilon > 0$:

$$u_\epsilon(x, t) = u(x, t) + \epsilon|x|^2.$$

Then: $u_\epsilon \in C_1^2(\Omega \times (0, T']) \cap C(\bar{\Omega} \times [0, \tilde{T}])$ and $\partial_t u_\epsilon - \Delta_x u_\epsilon < 0$ in $\Omega \times (0, \tilde{T}]$.
By Step 1:

$$\begin{array}{ccc} & \max_{\Omega_{\tilde{T}}} u_\epsilon \leq \max_{\partial^* \Omega_{\tilde{T}}} u_\epsilon & \\ \xRightarrow{\epsilon \rightarrow 0} & \max_{\Omega_{\tilde{T}}} u \leq \max_{\partial^* \Omega_{\tilde{T}}} u & \\ \xRightarrow{\tilde{T} \rightarrow T} & \max_{\Omega_T} u \leq \max_{\partial^* \Omega_T} u & \blacksquare \end{array}$$

Theorem 6.16 (Maximum principle for $\Omega = \mathbb{R}^d$) Let $\Omega_T = \mathbb{R}^d \times (0, T)$, $\bar{\Omega}_T = \mathbb{R}^d \times [0, T]$. Let $u \in C_1^2(\Omega_T) \cap C(\bar{\Omega}_T)$ such that

- $\partial_t u - \Delta_x u \leq 0$ in Ω_T
- $u(x, t) \leq M e^{M|x|^2}$ for all $(x, t) \in \bar{\Omega}_T$

Then

$$\sup_{(x,t) \in \bar{\Omega}_T} u(x, t) = \sup_{x \in \mathbb{R}^d} u(x, 0).$$

Proof.

Step 1: For all $y \in \mathbb{R}^d$ and $\epsilon > 0$ define

$$v(x, t) = u(x, t) - \frac{\epsilon}{(T + \epsilon - t)^{\frac{d}{2}}} \exp\left(\frac{|x - y|^2}{4(T + \epsilon - t)}\right)$$

This implies

$$\partial_t v - \Delta_x v = \partial_t u - \Delta_x u \leq 0$$

in Ω_T . For $U = B(y, r)$, $U_T = U \times (0, T)$, $\bar{U}_T = \bar{U} \times [0, T]$, $\partial^* U_T = (U \times \{0\}) \cup (\partial U \times [0, T])$, by the maximum principle for U bounded we have

$$\max_{\bar{U}_T} v \leq \max_{\partial^* U_T} v.$$

Let us bound $\max_{\partial^* U_T} v$.

- On $U \times \{0\}$ we use $v \leq u$ and hence

$$\max_{x \in \bar{U}} v(x, 0) \leq \max_{x \in \bar{U}} u(x, 0) \leq \max_{x \in \mathbb{R}^d} u(x, 0).$$

- On $\partial U \times [0, T]$ we use $|x - y| = r \Rightarrow |x| \leq |y| + r$.

$$\begin{aligned} v(x, t) &= u(x, t) - \frac{\epsilon}{(T + \epsilon - t)^{\frac{d}{2}}} \exp\left(\frac{|x - y|^2}{4(T + \epsilon - t)}\right) \\ &\leq M e^{M(|y|+r)^2} - \frac{\epsilon}{(T + \epsilon)^{\frac{d}{2}}} \exp\left(\frac{r^2}{4(T + \epsilon)}\right) \xrightarrow{r \rightarrow \infty} -\infty \end{aligned}$$

if $M < \frac{1}{4(T+\epsilon)}$. In particular, we can choose r large s.t.

$$\max_{\substack{x \in \partial U \\ t \in [0, T]}} v(x, t) \leq \max_{x \in \mathbb{R}^d} u(x, 0).$$

In summary, if $M < \frac{1}{4(T+\epsilon)}$, then:

$$u(y, t) - \frac{\epsilon}{(T + \epsilon - t)^{\frac{d}{2}}} = v(y, t) \leq \max_{\bar{U}_T} v \leq \max_{x \in \mathbb{R}^d} u(x, 0)$$

This holds for all $(y, t) \in \mathbb{R}^d \times [0, T]$. Thus,

$$\max_{\mathbb{R}^d \times [0, T]} u \leq \frac{\epsilon}{(T + \epsilon - t)^{\frac{d}{2}}} + \max_{x \in \mathbb{R}^d} u(x, 0)$$

Taking $\epsilon \rightarrow 0$ we conclude that if $M < \frac{1}{4T}$,

$$\max_{\mathbb{R}^d \times [0, T]} u \leq \max_{x \in \mathbb{R}^d} u(x, 0)$$

Step 2: For general T , we denote $T_1 = \frac{T}{N}$, $N \in \mathbb{N}$ s.t. $M < \frac{4}{T_1}$. Then by step 1:

$$\begin{aligned} \max_{\mathbb{R}^d \times [0, T_1]} u &\leq \max_{x \in \mathbb{R}^d} u(x, 0) \\ \max_{\mathbb{R}^d \times [T_1, 2T_1]} u &\leq \max_{x \in \mathbb{R}^d} u(x, T_1) \leq \max_{x \in \mathbb{R}^d} u(x, 0) \\ &\vdots \\ \max_{\mathbb{R}^d \times [(N-1)T_1, NT_1]} u &\leq \max_{x \in \mathbb{R}^d} u(x, (N-1)T_1) \leq \max_{x \in \mathbb{R}^d} u(x, 0) \\ \rightsquigarrow \max_{\mathbb{R}^d \times [0, T]} u &\leq \max_{x \in \mathbb{R}^d} u(x, 0) \end{aligned} \quad \blacksquare$$

Remark 6.17 The condition $u \leq Me^{M|x|^2}$ is necessary, otherwise there are solutions $u \neq 0$ s.t. $u(x, 0) = 0$

Theorem 6.18 (Uniqueness) If $u \in C_1^2(\mathbb{R}^d \times (0, T)) \cap C(\mathbb{R}^d \times [0, T])$ and

$$\begin{aligned} u(x, t) &\leq Me^{M|x|^2} && \text{in } \mathbb{R}^d \times [0, T], \\ \partial_t u - \Delta_x u &= 0 && \text{in } \mathbb{R}^d \times (0, T), \\ u(x, 0) &= 0 && \text{in } \mathbb{R}^d \end{aligned}$$

Then $u = 0$ in $\mathbb{R}^d \times [0, T]$.

Proof. Use the maximum principle for u and $-u$. ■

Remark 6.19 If $u(\cdot, t) \in L^2(\mathbb{R}^d)$, the proof of uniqueness can be done without the maximum principle. Heuristically:

$$\frac{d}{dt} \int_{\mathbb{R}^d} |u(x, t)|^2 dt = 2 \int_{\mathbb{R}^d} (\partial_t u) u dx = 2 \int_{\mathbb{R}^d} \Delta_x u u dx = -2 \int_{\mathbb{R}^d} |\nabla_x u|^2 dx \leq 0$$

This implies

$$e(t) := \int_{\mathbb{R}^d} |u(x, t)|^2 dx$$

is decreasing. Hence, if $e(0) = 0$, then $e(t) = 0$ for all $t \geq 0$. This argument will be helpful below for the heat backward equation.

Remark 6.20 The heat equation

$$\begin{cases} \partial_t u - \Delta_x u = 0 \\ u(t = 0) = g \end{cases}$$

is a well-posed problem:

- Existence
- Uniqueness
- Stability (solution depends continuously on data)

For the latter issue, by the maximum principle we have

$$\|u(\cdot, t)\|_{L^\infty} \leq \|u(\cdot, 0)\|_{L^\infty} \quad \forall t$$

or in the L^2 -situation:

$$\|u(\cdot, t)\|_{L^2} \leq \|u(\cdot, 0)\|_{L^2} \quad \forall t$$

On the other hand, the heat backward equation

$$\begin{cases} \partial_t u - \Delta_x u = 0 \\ u(t = T) = g \end{cases}$$

is *not* well-posed.

- Non-Existence: In general, the existence requires some special property on g , e.g. g is very smooth (only $g \in C(\mathbb{R}^d) \cap L^\infty(\mathbb{R}^d)$ or $g \in L^2(\mathbb{R}^d)$ is not enough)
- Uniqueness: On the other hand, the uniqueness still holds.

Lemma 6.21 If $e \in C^2(0, T)$, $e(t) \geq 0$, $e'(t) \leq 0$, $e''(t) \geq 0$ and $|e'(t)|^2 \leq e(t)e''(t)$ for $t \in [0, T]$ and $e(T) = 0$, then $e \equiv 0$.

Proof. Since e is monotonically decreasing and $e(T) = 0$ there is a $t_0 \in [0, T]$ s.t. $e(t_0) = 0$ and $e(t) > 0$ if $t \leq t_0$. We need to prove that $t_0 = 0$. Assume by contradiction $0 < t_0 \leq T$, then for $t \in (0, t_0)$ define $f(t) := \log e(t)$. Then

$$\begin{aligned} f'(t) &= \frac{e'(t)}{e(t)} \\ \Rightarrow f''(t) &= \frac{e''(t)e(t) - |e'(t)|^2}{e(t)^2} \geq 0 \end{aligned}$$

This means that f is convex, so for all $t_1, t_2 \in (0, t_0)$ and $\tau \in (0, 1)$:

$$\begin{aligned} f(\tau t_1 + (1 - \tau)t_2) &\leq \tau f(t_1) + (1 - \tau)f(t_2) \\ \Rightarrow e(\tau t_1 + (1 - \tau)t_2) &\leq e(t_1)^\tau e(t_2)^{1-\tau} \end{aligned}$$

Now, $e(\tau t_1 + (1 - \tau)t_2) \xrightarrow{t_2 \rightarrow t_0} 0$ and $\tau \rightarrow 1$ implies $e(t_1) = 0$ for all $t_1 \in (0, t_0)$ which is a contradiction. ■

Theorem 6.22 If $u \in C_1^2(\mathbb{R}^d \times [0, T]) \cap C^1(H^1(\mathbb{R}^d) \times [0, T])$ and

$$\begin{cases} \partial_t u - \Delta_x u = 0 & \text{in } \mathbb{R}^d \times (0, T) \\ u(x, T) = 0 \end{cases}$$

Then $u = 0$ in $\mathbb{R}^d \times [0, T]$.

Proof. Recall

$$e(t) = \int_{\mathbb{R}^d} |u(x, t)|^2 dx.$$

Then,

$$\begin{aligned} e'(t) &= 2 \int_{\mathbb{R}^d} u \partial_t u dx = 2 \int_{\mathbb{R}^d} u \Delta_x u dx = -2 \int_{\mathbb{R}^d} |\nabla_x u|^2 dx \\ e''(t) &= -4 \int_{\mathbb{R}^d} \nabla_x u \nabla_x (\partial_t u) = 4 \int_{\mathbb{R}^d} \Delta_x u \partial_t u dx = 4 \int_{\mathbb{R}^d} |\Delta_x u|^2 dx \geq 0 \end{aligned}$$

and hence

$$|e'(t)|^2 = 4 \left| \int_{\mathbb{R}^d} u \Delta_x u dx \right|^2 \leq 4 \left(\int_{\mathbb{R}^d} |u|^2 dx \right) \left(\int_{\mathbb{R}^d} |\Delta_x u|^2 dx \right) = e(t) e''(t)$$

Then the statement follows with lemma 6.21. ■

Some remarks about the eat equation in unbounded domains:

$$\begin{cases} \partial_t u - \Delta_x u = 0 & \text{in } \mathbb{R}^d \times (0, \infty) \\ u(x, 0) = 0 & \text{(i.e. } \lim_{t \rightarrow 0} u(x, t) = 0 \forall x \in \mathbb{R}^d) \end{cases}$$

There is a classical solution $0 \neq u \in C^1(\mathbb{R}^d \times (0, \infty))$. An example is

$$u(x, t) = \sum_{n=0}^{\infty} \frac{g^{(n)}(t)}{(2n)!} x^{2n}, \quad g(t) = e^{-\frac{1}{t^2}}$$

(s.t. $g \rightarrow 0$ as $t \rightarrow 0$). Note

$$\begin{aligned} g(t) &= e^{-\frac{1}{t^2}}, \\ g'(t) &= \frac{2}{t^3} g(t) \\ g''(t) &= \left(\frac{2}{t^3} \right)' g(t) + \frac{2}{t^3} \frac{2}{t^3} g(t) \\ g^{(n)}(t) &= P_n \left(\frac{1}{t} \right) g(t) \end{aligned}$$

where

$$\begin{cases} P_0 = 1 \\ P_{n+1} \left(\frac{1}{t} \right) = \left(P_n \left(\frac{1}{t} \right) \right)' + \left(\frac{2}{t^3} \right) P_n \left(\frac{1}{t} \right) = A_1 P_n + A_2 P_n, \begin{cases} A_1 = \partial_t \\ A_2 = \frac{2}{t^3} \end{cases} \\ P_{n+1} = (A_1 + A_2) P_n = (A_1 + A_2)(A_1 + A_2) P_{n-1} = \end{cases}$$

This implies:

$$P_n = (A_1 + A_2)^n P_0 = \sum_{\sigma \in \{1, 2\}^n} A_{\sigma(1)} A_{\sigma(2)} \cdots A_{\sigma(n)} P_0 \quad (6.1)$$

$$A_1 \left(\frac{\alpha}{t^s} \right) = \frac{-s\alpha}{t^{s+1}} \rightarrow A_1$$

Multiple coefficients by a factors and + power by 1

$$A_2 \left(\frac{\alpha}{t^s} \right) = \frac{2\alpha}{t^{s+3}} \rightarrow A_2$$

Mul Cof by a factor 2 and + power by 3

$$\left| \underbrace{A_{\sigma(1)} \cdots A_{\sigma(n)}, 1}_{k \text{ times } A_2, n-k \text{ times } A_1} \right| \leq \frac{2^k}{t^{3k}} \leq \frac{2^k}{t^{3k}} \frac{(3n)^{n-k}}{t^{n-k}} = \frac{2^k (3n)^{n-k}}{t^{n+2k}}$$

This implies

$$\left| P_n \left(\frac{1}{t} \right) \right| \leq \max_{0 \leq k \leq n} \frac{2^n 2^k (3n)^{n-k}}{t^{n+2k}}$$

Thus:

$$\begin{aligned} \sum_n \left| \frac{g^{(n)}(t)}{(2n)!} x^{2n} \right| &\leq \sum_n \max_{0 \leq k \leq n} \frac{2^n 2^k (3n)^{n-k}}{t^{n+2k} (2n)!} \frac{e^{-\frac{1}{t^2}}}{1} x^{2n} \\ &\leq \sum_n \max \frac{2^n 2^k (3n)^{n-k}}{t^{n+2k} (2n)!} (k!) (2t^2)^k e^{-\frac{1}{2t^2}} x^{2n} \\ &= \sum_n \frac{2^n 2^k 2^k (3n)^{n-k} (k!)}{(2n)! t^n} e^{-\frac{1}{2t^2}} x^{2n} \\ &\leq \sum_n \frac{(c_n)^n}{(2n)! t^n} e^{-\frac{1}{2t^2}} x^{2n} \\ &\leq \sum_n \frac{c^n}{n! t^n} e^{-\frac{1}{2t^2}} x^{2n} \\ &\leq \sum_n e^{\frac{c^2}{t} - \frac{1}{2t^2}} \end{aligned}$$

Where we used that

$$e^s = \sum_k \frac{s^k}{k!} \geq \frac{s^k}{k!}$$

for all $s \geq 0$ implies

$$e^{-\frac{1}{2t^2}} = \frac{1}{e^{\frac{1}{2t^2}}} \leq \frac{1}{\left(\frac{1}{2t^2}\right)^{\frac{1}{k!}}} = k! (2t^2)^k.$$

We conclude:

- $u(x, t)$ is well-defined, $x \in \mathbb{R}^d$, $t > 0$ real? to heat equation.
- $u(x, t) \rightarrow 0$ as $t \rightarrow 0$ for all $x \in \mathbb{R}^d$.

Exercise 6.23 (E 12.1) Let $\Omega \subseteq \mathbb{R}^d$ be open and $u \in C^2(\Omega)$. Assume that $x_0 \in \Omega$ is a local maximizer of u , namely there exists some $r > 0$ such that $u(x_0) \geq u(x)$ for all $x \in B_r(x_0) \subseteq \Omega$.

- (a) Prove that the Hessian matrix $H = (D^\alpha u(x_0))_{|\alpha|=2}$ is negative semi-definite, namely

$$yHy \leq 0$$

for all $y \in \mathbb{R}^d$.

- (b) Prove that $\Delta u(x_0) \leq 0$

Hint: Recall that we used (b) for the maximum principle by Hopf's method.

Solution. (a) In 1D this is obvious. If x_0 is a local minimizer of u , then $u'(x_0) = 0, u''(x_0) \leq 0$ (Taylor expansion).

In d dimensions:

$$\phi(t) = u(x_0 + t\xi) \quad \xi \in \mathbb{R}^d, t \in \mathbb{R}, |t| \text{ small}$$

So 0 is a local maximizer of ϕ . This implies

$$0 = \phi'(0) = \nabla u(x_0)\xi \quad \forall \xi \in \mathbb{R}^d \Rightarrow H \leq 0$$

$$\begin{aligned} \phi''(0) &= \lim_{t \rightarrow 0} \frac{\phi'(t) - \phi'(0)}{t} = \lim_{t \rightarrow 0} \frac{(\nabla u(x_0 + t\xi) - \nabla u(x_0))\xi}{t} \\ &= \lim_{t \rightarrow 0} \sum_{i=1}^d \frac{(\partial_i u(x_0 + t\xi) - \partial_i u(x_0))\xi_i}{t} = \sum_{i=1}^d \sum_{j=1}^d \partial_j \partial_i u(x_0) \xi_j \xi_i = \langle \xi, H\xi \rangle, \end{aligned}$$

$$H = (\partial_i \partial_j u(x_0))_{i,j=1}^d.$$

(b) Consequently

$$\Delta u(x_0) = \sum_{i=1}^d \partial_i \partial_i u(x_0) = \text{Tr}(H) \leq 0 \quad \blacksquare$$

Exercise 6.24 (E 12.2) Let $\Omega \subseteq \mathbb{R}^d$ be open and bounded. We prove the maximum principle for a general elliptic operator

$$Lu(x) = \sum_{i,j=1}^d a_{ij}(x) \partial_i \partial_j u(x) + \sum_{i=1}^d b_i(x) \partial_i u(x),$$

$a_{ij}, b_i \in C(\bar{\Omega})$, $A(x) = (a_{ij}(x))_{i,j=1}^d \geq \mathbb{1}$ (as matrices). Prove that if $Lu(x) \geq 0$ for all $x \in \Omega$ and $u \in C^2(\Omega) \cap C(\bar{\Omega})$, then

$$\max_{x \in \bar{\Omega}} u(x) = \max_{x \in \partial\Omega} u(x).$$

Solution.

Step 1: Assume $Lu(x) > 0$ for all $x \in \Omega$: Since $u \in C(\bar{\Omega})$ there is a $x_0 \in \bar{\Omega}$ s.t.

$$u(x_0) = \max_{x \in \bar{\Omega}} u(x).$$

We prove $x_0 \in \partial\Omega$. Assume by contradiction that $x_0 \notin \partial\Omega$, so $x_0 \in \Omega$ is a local maximizer. We prove $Lu(x_0) \leq 0$. Note:

$$\begin{aligned} Lu(x_0) &= \sum_{i,j=1}^d a_{ij}(x_0) \partial_i \partial_j u(x_0) + \sum_{i=1}^d b_i(x_0) \partial_i u(x_0) \\ &= \text{Tr}[A(x_0)H(x_0)] + B(x_0) \underbrace{\nabla u(x_0)}_{=0} \leq 0 \quad \nexists \end{aligned}$$

$$A(x_0) = (a_{ij}(x_0))_{i,j=1}^d, B(x_0) = (b_i(x_0))_{i=1}^d, \text{ where } \text{Tr}[AH] = \sum_i (AH)_{ii} = \sum_i \sum_j A_{ij} H_{ji}$$

General fact: If $A \geq 0, B \geq 0$ (matrices), then $\text{Tr}(AB) \geq 0$.

$$\bullet A = (\sqrt{A})^2 \Rightarrow \text{Tr}(AB) = \text{Tr}((\sqrt{A})^2 B) = \text{Tr}(\underbrace{\sqrt{A} B \sqrt{A}}_{\geq 0}) \geq 0$$

- Spectral theorem: $A \geq 0$, then there are eigenvectors (α_i) and eigenvalues $\lambda_i \geq 0$ s.t.

$$\text{Tr}(AB) = \sum_i \langle \alpha_i, AB\alpha_i \rangle = \sum_i \underbrace{\lambda_i}_{\geq 0} \underbrace{\langle \alpha_i, B\alpha_i \rangle}_{\geq 0} \geq 0$$

- General Case: $Lu(x) \geq 0$ for all $x \in \Omega$. Assume that there is a $v \in C^2(\Omega) \cap C(\bar{\Omega})$ s.t. $Lv(x) > 0$ for all $x \in \Omega$. Define for all $\epsilon > 0$ $u_\epsilon = u + \epsilon v$. Then $Lu_\epsilon(x) = Lu(x) + \epsilon Lv(x) > 0$ for all $x \in \Omega$. By Step 1,

$$\begin{aligned} \max_{x \in \bar{\Omega}} u_\epsilon(x) &\leq \max_{x \in \partial\Omega} u_\epsilon(x) \\ \xrightarrow{\epsilon \rightarrow 0} \max_{x \in \bar{\Omega}} u(x) &\leq \max_{x \in \partial\Omega} u(x) \end{aligned}$$

What v ? First $v(x) = x^2 = x_1^2 + \dots + x_d^2$,

$$Lv(x) = \sum_{ij} a_{ij}(x) 2\delta_{ij} + \sum_i b_i(x) 2x_i$$

not clear to be ≥ 0 .

$$\begin{aligned} v(x) &= x^{2n} \quad n \text{ large} \\ v(x) &= x_1^{2n} \longrightarrow Lv(x) = a_{11}(x) 2n(2n+1)x_1^{2n-2} + b_1(x) 2nx_1^{2n-1} \\ &\geq 2nx_1^{2n-2} [(2n-1) + \underbrace{b_1(x)x_1}_{\substack{\text{b.d. in } \bar{\Omega} \\ > 0}}] \geq 0 \quad \forall x \in \bar{\Omega} \end{aligned}$$

if n is large enough.

$$v(x) = (x_1 + R)^{2n}$$

where $R > 0$ large s.t. $x_1 + R \geq 1$ for all $\forall x \in \bar{\Omega}$. This implies

$$Lv(x) \geq 2n \underbrace{(x_1 + R)^{2n-2}}_{> 0} \underbrace{[2n-1 + b_1(x)(x_1 + R)]}_{> 0} > 0$$

for all $x \in \bar{\Omega}$ if n is large. ■

Exercise 6.25 (E 12.3) Consider the inhomogeneous heat equation

$$\begin{cases} \partial_t u - \Delta_x u = f(x, t) & \text{in } \mathbb{R}^d \times (0, T) \\ u(t=0) = g & \text{in } \mathbb{R}^d \end{cases},$$

$f \in C_1^2(\mathbb{R}^d \times (0, T))$ and compactly supported and $g \in C(\mathbb{R}^d \times [0, T]) \cap L^\infty(\mathbb{R}^d \times [0, T])$. Assume that there exists a solution $u \in C_1^2(\mathbb{R}^d \times (0, T)) \cap C(\mathbb{R}^d \times [0, T])$ satisfying

$$u(x, t) \leq Me^{M|x|^2}, \quad (x, t) \in \mathbb{R}^d \times [0, T].$$

Prove that

$$\max_{(x,t) \in \mathbb{R}^d \times [0,T]} |u(x, t)| \leq \|g\|_{L^\infty} + T\|f\|_{L^\infty}.$$

Solution.

Step 1: There is at most one solution u .

Step 2:

$$u(x, t) = \int_{\mathbb{R}^d} \phi(x - y, t) g(y) dy + \int_0^t \int_{\mathbb{R}^d} \phi(x - y, t - s) f(y, s) dy ds$$

This implies:

$$\begin{aligned} \|u\|_{L^\infty} &\leq \int_{\mathbb{R}^d} \phi(x - y, t) \|g\|_{L^\infty} dy + \int_0^t \int_{\mathbb{R}^d} \phi(x - y, t - s) \|f\|_{L^\infty} dy ds \\ \Rightarrow \|u\|_{L_{x,t}^\infty} &\leq \int_{\mathbb{R}^d} \phi(x - y, t) \|g\|_{L^\infty} dy + \int_0^T \int_{\mathbb{R}^d} \phi(x - y, t - s) \|f\|_{L^\infty} dy ds \\ &= \|g\|_{L_x^\infty} + T \|f\|_{L_{x,t}^\infty} \end{aligned}$$

This is optimal! E.g. $g = 0, f = 1, u(x, t) = u(t)$.

$$\begin{cases} u' = 1 \\ u(0) = 0 \end{cases} \Rightarrow u(t) = t$$

■

Exercise 6.26 (Bonus 11) Denote for all $u \in C^2(\Omega) \cap C(\bar{\Omega})$:

$$Lu(x) = \sum_{i,j=1}^d a_{ij}(x) \partial_i \partial_j u(x)$$

where $a_{ij} \in C(\bar{\Omega})$ s.t. $A(x) = (a_{ij}(x)) \geq 1$. Prove that if $\Omega \subseteq \mathbb{R}^d$ is open and bounded, $u \in C_1^2(\bar{\Omega} \times [0, T])$ and

$$\begin{cases} \partial_t u - Lu \leq 0 & \text{in } \Omega \times (0, T) \\ u(t = 0) = 0 \\ u(x \in \partial\Omega) = 0 \end{cases}$$

Prove that $u(x, t) \leq 0$ for all $(x, t) \in \bar{\Omega} \times [0, T]$.

6.3 Backward heat equation

Theorem 6.27 (Instability)

There exist functions $u_\epsilon \in C_1^2(\mathbb{R}^d \times (0, T)) \cap C^1(H^1(\mathbb{R}^d) \times [0, T])$ s.t.

$$\partial_t u_\epsilon - \Delta_x u_\epsilon = 0 \quad \text{in } \mathbb{R}^d \times [0, T]$$

with:

$$\|u_\epsilon(\bullet, T)\|_{L^2(\mathbb{R}^d)} \xrightarrow{\epsilon \rightarrow 0^+} 0, \quad \|u_\epsilon(\bullet, 0)\|_{L^2(\mathbb{R}^d)} \xrightarrow{\epsilon \rightarrow 0^+} \infty.$$

Proof. Recall by Fourier Transform

$$\begin{aligned} &\partial_t \hat{u}(k, t) + |2\pi k|^2 \hat{u}(k, t) = 0 \\ \Leftrightarrow &\partial_t (e^{|2\pi k|^2 t} \hat{u}(k, t)) = 0 \\ \Rightarrow &e^{|2\pi k|^2 t} \hat{u}(k, t) = u(k, 0) \\ \Rightarrow &\hat{u}(k, t) = e^{-t|2\pi k|^2} \hat{u}(k, 0) \\ \Rightarrow &\hat{u}(k, 0) = e^{T|2\pi k|^2} \hat{u}(k, T). \end{aligned}$$

Now we can take

$$\hat{u}_\epsilon(k, t) = \mathbb{1}\left(|k| \leq \frac{1}{\epsilon}\right) \epsilon^{d+1} dk$$

Then,

$$\begin{aligned} \|u(\bullet, T)\|_{L^2(\mathbb{R}^d)}^2 &= \int_{\mathbb{R}^d} \hat{u}_\epsilon(k, t) dk = \lambda^d(\{|k| \leq \epsilon^{-1}\}) \epsilon^{d+1} \sim \epsilon \xrightarrow{\epsilon \rightarrow 0} 0 \\ \|u(\bullet, 0)\|_{L^2(\mathbb{R}^d)}^2 &= \int_{\mathbb{R}^d} e^{2T|2\pi k|^2} \mathbb{1}(|k| \leq \epsilon^{-1}) \epsilon^{d+1} dk \\ &\geq \int_{\frac{\epsilon}{2} \leq |k| \leq \frac{\epsilon}{2}} e^{2T|2\pi k|^2} \mathbb{1}(|k| \leq \epsilon^{-1}) \epsilon^{d+1} dk \gtrsim e^{2T\epsilon^{-2}} \epsilon \xrightarrow{\epsilon \rightarrow 0} \infty \end{aligned}$$

■

Remark 6.28 This means that a small error of the data at $t = T$ may cause a large error of the output $t = 0$.

Theorem 6.29 (Regularized solution)

Assume that $u \in C_1^2(\mathbb{R}^d \times (0, T)) \cap C^1(H^1(\mathbb{R}^d), [0, T])$

$$\begin{cases} \partial_t u - \Delta_x u = 0 & \text{in } \mathbb{R}^d \times (0, T) \\ u(x, T) = g(x) & \text{in } \mathbb{R}^d \end{cases}$$

Then from given data $g_\epsilon \in L^2(\mathbb{R}^d)$ s.t.

$$\|g_\epsilon - g\|_{L^2(\mathbb{R}^d)} \leq \epsilon$$

we construct a solution \tilde{u}_ϵ s.t.

$$\sup_{t \in [0, T]} \|\tilde{u}_\epsilon(\bullet, t) - u(\bullet, t)\|_{L^2(\mathbb{R}^d)} \xrightarrow{\epsilon \rightarrow 0} 0$$

Proof. Clearly we should not choose \tilde{u}_ϵ to solve

$$\begin{cases} \partial_t u_\epsilon - \Delta_x u_\epsilon = 0 \\ u_\epsilon(t = T) = g_\epsilon \end{cases},$$

i.e.

$$\hat{u}_\epsilon(k, t) = e^{(T-t)|2\pi k|^2} \hat{g}_\epsilon(k).$$

Rather we take

$$\hat{u}_\epsilon(k, t) = e^{(T-t)|2\pi k|^2} \hat{g}_\epsilon(k) \mathbb{1}(|k| \leq \delta_\epsilon^{-1})$$

Where $\delta_\epsilon \rightarrow 0$ (chosen later). Then we have for all $t \in [0, T]$:

$$\begin{aligned} \|u_\epsilon(\bullet, t) - u(\bullet, t)\|_{L^2(\mathbb{R}^d)}^2 &= \int_{\mathbb{R}^d} e^{2(T-t)|2\pi k|^2} |\hat{g}_\epsilon(k) \mathbb{1}(|k| \leq \delta_\epsilon^{-1}) - \hat{g}(k)|^2 dk \\ &\leq 2 \int_{\mathbb{R}^d} e^{2T|2\pi k|^2} |\hat{g}_\epsilon(k) - \hat{g}(k)|^2 \mathbb{1}(|k| \leq \delta_\epsilon^{-1}) dk \\ &\quad + 2 \int_{\mathbb{R}^d} \underbrace{e^{2T|2\pi k|^2} |\hat{g}(k)|^2}_{|\hat{u}(k, 0)|^2} \mathbb{1}(|k| > \delta_\epsilon^{-1}) dk = \text{(I)} + \text{(II)} \end{aligned}$$

We have

$$\begin{aligned} \text{(I)} &\leq 2 \int_{\mathbb{R}^d} e^{c\delta_\epsilon^{-2}} |\hat{g}_\epsilon(k) - \hat{g}(k)|^2 dk = 2e^{c\delta_\epsilon^{-2}} \epsilon^{-2} \longrightarrow 0 && \text{if } \delta_\epsilon \gg \frac{1}{\sqrt{|\log \epsilon|}} \\ \text{(II)} &= 2 \int_{\mathbb{R}^d} |\hat{u}(k, 0)|^2 \mathbb{1}(|k| \geq \delta_\epsilon^{-1}) dk \leq 2 \int_{\mathbb{R}^d} |k|^2 \delta_\epsilon^2 |\hat{u}(k, 0)|^2 dk \end{aligned}$$

Thus choosing $\frac{1}{\sqrt{|\log \epsilon|}} \ll \delta_\epsilon \ll 1$, e.g. $\delta_\epsilon = (|\log \epsilon|)^{-\frac{1}{4}}$.

$$\sup_{t \in [0, T]} \|u_\epsilon(\bullet, t) - u(\bullet, t)\|_{L^2(\mathbb{R}^d)} \leq \text{(I)} + \text{(II)} \xrightarrow{\epsilon \rightarrow 0} 0 \quad \blacksquare$$

Remark 6.30 In application, both u and g are unknown. Only g_ϵ is given. So we have to construct \tilde{u}_ϵ using only information from g_ϵ .

Chapter 7

Wave Equation

7.1 d'Alembert

Wave equation:

$$\begin{cases} \partial_t^2 u - \Delta_x u = 0 & x \in \mathbb{R}^d, t > 0 \\ u = g, \partial_t u = h & x \in \mathbb{R}^d, t = 0 \end{cases}$$

In $d = 1$:

$$\begin{cases} \partial_t^2 u - \partial_x^2 u = 0, & (x, t) \in \mathbb{R} \times (0, \infty) \\ u = g, \partial_t u = h, & x \in \mathbb{R}, t = 0 \end{cases}$$

Key idea: Factorization:

$$\partial_t^2 - \partial_x^2 = (\partial_t + \partial_x)(\partial_t - \partial_x).$$

Then, if we denote $v = (\partial_t - \partial_x)u$, we get the transport equation

$$(\partial_t + \partial_x)v = 0.$$

This implies

$$v(x, t) = a(x - t), \quad a(x) = v(x, 0)$$

From this we get the inhomogeneous transport equation

$$(\partial_t - \partial_x)u = a(x - t).$$

Now we decompose $u = u_1 + u_2$, where

$$\begin{cases} (\partial_t - \partial_x)u_1 = 0 \\ (\partial_t - \partial_x)u_2 = a(x - t) \end{cases}.$$

Like above, we get $u_1 = b(x + t)$ and an explicit choice of u_2 is

$$u_2(x, t) = \frac{1}{2} \int_{x-t}^{x+t} a(y) dy$$

Thus,

$$u(x, t) = b(x + t) + \frac{1}{2} \int_{x-t}^{x+t} a(y) dy$$

Let's compute a and b :

$$\begin{aligned} b(x) &= u(x, 0) = g(x) \\ a(x) &= v(x, 0) = (\partial_t u - \partial_x u)_{t=0} = h - g'. \end{aligned}$$

Theorem 7.1 (d'Alembert formula) For $d = 1$ let $g \in C^2(\mathbb{R}^d)$, $h \in C^1(\mathbb{R})$ and define u by the *d'Alembert formula*

$$\begin{aligned} u(x, t) &= \int_{x-t}^{x+t} (h(y) - g'(y)) dy + g(x+t) \\ &= \frac{1}{2}[g(x+t) + g(x-t)] + \frac{1}{2} \int_{x-t}^{x+t} h(y) dy. \end{aligned}$$

Then:

- $u \in C^2(\mathbb{R} \times (0, \infty))$
- $\partial_t^2 u - \partial_x^2 u = 0$
- $u = g, \partial_t u = h$ when $t \rightarrow 0$

Proof. Exercise. ■

Remark 7.2 If $g \in C^k$ and $h \in C^{k-1}$, then $u \in C^k$ (but not better).

Now, let's apply the *Reflection Method*. Replace \mathbb{R} by $\mathbb{R}_+ = (0, \infty)$ and assume

$$\begin{cases} \partial_t^2 u - \partial_x^2 u = 0 & \mathbb{R}_+ \times (0, \infty) \\ u = g, \partial_t u = h & \text{on } \mathbb{R}_+ \times \{t = 0\}, g(0) = h(0) = 0 \\ u = 0 & \text{on } \{x = 0\} \times \{t > 0\} \end{cases}$$

Define

$$\begin{aligned} \tilde{u}(x, t) &= \begin{cases} u(x, t), & x \geq 0, t \geq 0 \\ -u(-x, t), & x \leq 0, t \geq 0 \end{cases} \\ \tilde{g}(x) &= \begin{cases} g(x) & x \geq 0 \\ -g(-x) & x \leq 0 \end{cases} \\ \tilde{h}(x) &= \begin{cases} h(x) & x \geq 0 \\ -h(-x) & x \leq 0 \end{cases} \end{aligned}$$

Then

$$\begin{cases} \partial_t^2 \tilde{u} - \partial_x^2 \tilde{u} = 0 & \text{in } \mathbb{R} \times (0, \infty) \\ \tilde{u} = \tilde{g}, \partial_t \tilde{u} = \tilde{h} & \text{on } \mathbb{R} \times \{t = 0\} \end{cases}.$$

By d'Alembert formula

$$\tilde{u}(x, t) = \frac{1}{2} [\tilde{g}(x+t) + \tilde{g}(x-t)] + \frac{1}{2} \int_{x-t}^{x+t} \tilde{h}(y) dy$$

This implies

$$u(x, t) = \begin{cases} \frac{1}{2}[g(x+t) + g(x-t)] + \frac{1}{2} \int_{x-t}^{x+t} h(y) dy & x \geq t \geq 0 \\ \frac{1}{2}[g(x+t) - g(t-x)] + \frac{1}{2} \int_{t-x}^{x+t} h(y) dy & t \geq x \geq 0 \end{cases}.$$

This is the solution of the heat equation in $\mathbb{R}_+ \times (0, \infty)$.

7.2 Euler-Poisson-Darboux

$$(\star) \quad \begin{cases} \partial_t^2 u - \Delta_x u = 0 & \text{in } \mathbb{R}^d \times (0, \infty) \\ u = g, \partial_t u = h & \mathbb{R}^d \times \{t = 0\} \end{cases}$$

Idea: Averaging of u over sphere \rightsquigarrow 1D problem. Define for $x \in \mathbb{R}^d$, $t > 0$, $r > 0$,

$$\begin{aligned} U_r(x, t) &:= \oint_{\partial B(x, r)} u(y, t) dS(y) \\ G_r(x) &:= \oint_{\partial B(x, r)} g(y) dS(y) \\ H_r(x) &:= \oint_{\partial B(x, r)} h(y) dS(y) \end{aligned}$$

Lemma 7.3 (Euler-Poisson-Darboux equation) If $u \in C^2(\mathbb{R}^d \times [0, \infty))$ solves (\star) , then for all $x \in \mathbb{R}^d$:

$$\begin{aligned} &\bullet (r, t) \mapsto U \in C^2([0, \infty) \times [0, \infty)) \\ &\bullet \begin{cases} \partial_t^2 U - \partial_r^2 U - \frac{d-1}{r} \partial_r U = 0 & \text{in } \mathbb{R}_+ \times \mathbb{R}_+ \\ U = G, \partial_t U = H & \text{on } \mathbb{R}_+ \times \{t = 0\} \end{cases} \end{aligned}$$

Note that $\partial_r^2 + \frac{d-1}{r} \partial_r$ is the radial part of Δ .

Proof. We compute for $r > 0$:

$$\begin{aligned} \partial_r U_r(x, t) &= \partial_r \oint_{\partial B(x, r)} u(y, t) dS(y) \\ &= \partial_r \oint_{\partial B(0, 1)} u(x + rz, t) dS(z) \\ &= \oint_{\partial B(0, 1)} \nabla u(x + rz, t) z dS(z) \\ &= \oint_{\partial B(x, r)} \nabla u(y, t) \frac{y - x}{r} dS(y) \\ &= \oint_{\partial B(x, r)} \frac{\partial u(y, t)}{\partial \vec{n}} dS(y) \\ \text{(Green 2.3)} \quad &= \frac{1}{|\partial B(0, r)|} \int_{B(x, r)} \Delta_x u(y, t) dy \\ \left(|B(0, r)| = \frac{r}{d} |\partial B(0, r)| \right) \quad &= \frac{r}{d} \oint_{\partial B(x, r)} \Delta_x u(y, t) dy \end{aligned}$$

(The computation is similar to the proof of the mean-value theorem for the Poisson equation.) We compute the second derivative

$$\begin{aligned} \partial_r^2 U_r(x, t) &= \partial_r \left[\frac{r}{d} \oint_{\partial B(x, r)} \Delta_x u(y, t) dy \right] \\ \left(|B(0, r)| = r^d |B(0, 1)| \right) \quad &= \partial_r \left[\frac{1}{d |B_1| r^{d-1}} \int_{\partial B(x, r)} \Delta_x u(y, t) dy \right] \end{aligned}$$

Now, $\partial_r \frac{1}{d|B_1|r^{d-1}} = \frac{-d+1}{d|B_1|r^d} = -\frac{d-1}{d|B(0,r)|}$ and

$$\begin{aligned}
\partial_r \int_{B(x,r)} \Delta_x u(y,t) dS(y) &= \partial_r \int_{B(0,r)} \Delta_x u(x+ry,t) dy \\
(\text{Green 2.3}) \quad &= \partial_r \int_{\partial B(0,1)} \nabla_x u(x+ry,t) \frac{y}{|y|} dS(y) \\
(|y|=1) \quad &= \int_{\partial B(0,1)} \partial_r \nabla_x u(x+ry,t) y dS(y) \\
&= \int_{\partial B(0,1)} \Delta_x u(x+ry,t) y \cdot y dS(y) \\
(y \cdot y = |y|^2 = 1) \quad &= \int_{\partial B(0,1)} \Delta_x u(x+ry,t) dS(y) \\
&= \int_{\partial B(x,r)} \Delta_x u(y,t) dS(y)
\end{aligned}$$

Now with the product rule we get

$$\begin{aligned}
\partial_r^2 U_r(x,t) &= -\left(\frac{d-1}{d}\right) \oint_{B(x,r)} \Delta_x u(y,t) dy \\
&\quad + \frac{1}{d|B_1|r^{d-1}} \int_{\partial B(x,r)} \Delta_x u(y,t) dS(y) \\
&= -\left(\frac{d-1}{d}\right) \oint_{B(x,r)} \Delta_x u(y,t) dy \\
&\quad + \oint_{\partial B(x,r)} \Delta_x u dS(y)
\end{aligned}$$

And, since u is a solution,

$$\partial_t^2 U = \partial_t^2 \oint_{\partial B(x,r)} u dS(y) = \oint_{\partial B(x,r)} (\partial_t^2 u) dS(y) = \oint_{\partial B(x,r)} (\Delta_x u) dS(y).$$

So we can conclude

$$\partial_t^2 U - \partial_r^2 U - \frac{d-1}{d} U = 0$$

the above computation also shows that $U \in C^2(\mathbb{R}_+ \times [0, \infty))$. Moreover

$$\begin{aligned}
\partial_r U_r(x,t) &\xrightarrow{r \rightarrow 0^+} 0 \\
\partial_r^2 U_r(x,t) &\xrightarrow{r \rightarrow 0^+} \left(\frac{1}{d} - 1\right) \Delta_x u + \Delta_x u = \frac{1}{d} \Delta_x u
\end{aligned}$$

This implies that $U \in C^2([0, \infty) \times [0, \infty))$. Finally, when $t = 0$,

$$\begin{cases} u = g \\ \partial_t = h \end{cases} \Rightarrow \begin{cases} U = G \\ \partial_t U = H \end{cases} \quad \blacksquare$$

We showed that it is a necessary condition for u to solve the Euler-Poisson-Darboux equation. Now we try to actually solve the equation. In general, this is easier for odd d than for even d . We will consider the cases $d = 2, 3$.

7.2.1 Solution in three dimensions

Now, for $r > 0$ let $\tilde{U} = rU, \tilde{G} = rG, \tilde{H} = rH$. Then

$$\begin{cases} \partial_t^2 \tilde{U} - \partial_r^2 \tilde{U} = 0 & \text{in } \mathbb{R}_+ \times (0, \infty) \\ \tilde{U} = \tilde{G}, \partial_t \tilde{U} = \tilde{H} & \text{when } t = 0 \\ \tilde{U} = 0 & \text{when } r = 0 \end{cases}$$

Then, by d'Alembert's formula, for $0 \leq r \leq t$ we have

$$\begin{aligned} \tilde{U}_r(x, t) &= \frac{1}{2} \left[\tilde{G}(r+t) - \tilde{G}(t-r) \right] + \frac{1}{2} \int_{t-r}^{t+r} \tilde{H}(y) dy. \\ \Rightarrow U_r(x, t) &= \frac{1}{2} \left[\frac{\tilde{G}(r+t) - \tilde{G}(t-r)}{r} \right] + \frac{1}{2r} \int_{t-r}^{t+r} \tilde{H}(y) dy \end{aligned}$$

Now, taking $r \rightarrow 0$ we get

$$\begin{aligned} u(x, t) &= \tilde{G}'(t) + \tilde{H}(t) \\ &= \partial_t \left(t \oint_{\partial B(x, t)} g(y) dS(y) \right) + t \oint_{\partial B(x, t)} h(y) dS(y) \end{aligned}$$

Using

$$\oint_{\partial B(x, t)} g(y) dS(y) = \oint_{\partial B(0, 1)} g(x + tz) dS(z)$$

we get

$$\begin{aligned} \partial_t \oint_{\partial B(x, t)} g(y) dS(y) &= \oint_{\partial B(0, 1)} \nabla g(x + tz) z dz \\ &= \oint_{\partial B(x, t)} \nabla g(y) \left(\frac{y - x}{t} \right) dS(y) \\ \Rightarrow \partial_t \left(t \oint_{\partial B(x, t)} g(y) dS(y) \right) &= \oint_{\partial B(x, t)} (g + \nabla g(y - x)) dS(y) \end{aligned}$$

From that we get:

Remark 7.4 (Kirchhoff's formula in 3D) For all $x \in \mathbb{R}^3, t > 0$:

$$u(x, t) = \oint_{\partial B(x, t)} (g(y) + \nabla g(y - x) + th(y)) dS(y)$$

7.2.2 Solution in two dimensions

The transformation $\tilde{U} = rU$ does not work! The idea is to think of the 2D problem as 3D problem with x_3 hidden. We write $\bar{u}(x_1, x_2, x_3, t) = u(x_1, x_2, t)$. Then we get

$$\begin{cases} \partial_t^2 \bar{u} - \Delta_x \bar{u} = 0 & \text{in } \mathbb{R}^d \times (0, \infty) \\ \bar{u} = \bar{g}, \partial_t \bar{u} = \bar{h} & \text{on } \mathbb{R}^3 \times \{t = 0\} \end{cases}$$

With Kirchhoff's formula:

$$u(x, t) = \bar{u}(\bar{x}, t) = \partial_t \left(t \oint_{\partial \bar{B}(\bar{x}, t)} \bar{g}(y) d\bar{S}(y) \right) + t \int_{\partial \bar{B}(\bar{x}, t)} \bar{h} d\bar{S}(y)$$

Let $\gamma(y) = (t^2 - |y - x|^2)^{\frac{1}{2}}, y \in B(x, t)$, then

$$\begin{aligned} \oint_{\partial \bar{B}(\bar{x}, t)} \bar{g} d\bar{S} &= \frac{1}{4\pi t^2} \int_{\partial \bar{B}(\bar{x}, t)} \bar{g} d\bar{S}(y) \\ &= \frac{1}{4\pi t^2} \int_{B(x, t)} g(y) 2(1 + |\nabla \gamma|^2)^{\frac{1}{2}} dy \\ &= \frac{1}{4\pi t^2} \int_{B(x, r)} g(y) \frac{2t}{\sqrt{t^2 - |y - x|^2}} dy \\ &= \frac{t}{2} \oint_{B(x, t)} \frac{g(y)}{\sqrt{t^2 - |y - x|^2}} dy \end{aligned}$$

Similarly:

$$\oint_{\partial B(\bar{x}, t)} \bar{h} d\bar{S}(y) = \frac{t}{2} \oint_{B(x, t)} \frac{h(y)}{\sqrt{t^2 - |y - x|^2}} dy$$

This implies:

$$\begin{aligned} u(x, t) &= \partial_t \left(\frac{t^2}{2} \oint_{B(x, t)} \frac{g(y)}{(t^2 - |y - x|^2)^{\frac{1}{2}}} dy \right) + \frac{t^2}{2} \oint_{B(x, r)} \frac{h(y)}{(t^2 - |y - x|^2)^{\frac{1}{2}}} dy \\ &= (I) + (II) \\ (I) &= \partial_t \left(\frac{1}{2} t \oint_{B(0, 1)} \frac{g(x + tz)}{(1 - |z|^2)^{\frac{1}{2}}} dz \right) \\ &= \oint_{B(0, 1)} \frac{g(x + tz)}{(1 - |z|^2)^{\frac{1}{2}}} dz + t \oint_{B(0, 1)} \frac{\nabla g(x + tz) z}{(1 - |z|^2)^{\frac{1}{2}}} dz \\ &= t \int_{B(x, t)} \frac{g(y)}{\sqrt{t^2 - |y - x|^2}} dy + t \oint_{B(x, r)} \frac{\nabla g(y)(y - x)}{\sqrt{t^2 - |y - x|^2}} dy \end{aligned}$$

Remark 7.5 (Poisson formula for 2D) For $x \in \mathbb{R}^2, t > 0$ we have

$$u(x, t) = \frac{t}{2} \oint_{B(x, t)} \frac{g(y) + \nabla g(y)(y - x) + th(y)}{(t^2 - |y - x|^2)^{\frac{1}{2}}} dy.$$

7.3 Spectral Method

Let $\Omega \subseteq \mathbb{R}^d$ be open and bounded.

$$\begin{cases} \partial_t^2 u - \Delta_x u = 0 & \text{in } \Omega \times (0, \infty) \\ u = g, \partial_t u = h & \text{when } t = 0 \\ u = 0 & \text{when } x \in \partial\Omega \end{cases}$$

$-\Delta$ has eigenvecors $(e_i)_{i=1}^\infty$ with eigenvalues $(\lambda_i)_{i=1}^\infty$, i.e.

$$\begin{cases} -\Delta e_i = \lambda_i e_i \\ e_i|_{\partial\Omega} = 0 \end{cases}$$

s.t. $\lambda_1 < \lambda_2 \leq \dots \leq \lambda_i \rightarrow \infty$ and $(e_i)_{i \in \mathbb{N}}$ is an orthonormal basis for $L^2(\Omega)$. We write

$$u(x, t) = \sum_{i \in \mathbb{N}} a_i(t) e_i(x)$$

This implies:

$$a_i''(t) + \lambda_i a_i(t) = 0$$

$$(\text{ODE}) \quad \Rightarrow \quad a_i(t) = a_i(0) \cos(\sqrt{\lambda_i}t) + \frac{a_i'(0)}{\sqrt{\lambda_i}} \sin(\sqrt{\lambda_i}t)$$

Here $a_i(0)$, $a_i'(0)$ is determined by

$$\begin{cases} g = u(t=0) = \sum_{i=1}^{\infty} a_i(0) e_i(x) \\ h = \partial_t u(t=0) = \sum_{i=1}^{\infty} a_i'(0) e_i(x) \end{cases} \Rightarrow \begin{cases} a_i(0) = \langle e_i, g \rangle \\ a_i'(0) = \langle e_i, h \rangle \end{cases}$$

7.4 Uniqueness

For $\Omega \subseteq \mathbb{R}^d$ open and bounded with C^1 -boundary regard

$$\begin{cases} \partial_t^2 u - \Delta_x u = 0 & \text{in } \Omega \times (0, T) \\ u = 0, \partial_t u = 0 & \text{in } \Omega \times \{t = 0\} \\ u = 0 & \partial\Omega \times [0, T] \end{cases}.$$

If $u \in C^2(\bar{\Omega} \times [0, T])$, then $u = 0$.

Proof. Let

$$e(t) = \int_{\Omega} (|\partial_t u|^2 + |\nabla_x u|^2) dx$$

has $e'(t) = 0$. This implies $e(t) = e(0) = 0$, so $\partial_t u = 0$ and hence $u = 0$. ■

The same result holds for \mathbb{R}^d , i.e.

$$\begin{cases} \partial_t^2 u - \Delta_x u = 0 & \mathbb{R}^d \times (0, T) \\ u = 0, \partial_t u = 0 & \mathbb{R}^d \times \{t = 0\} \end{cases}$$

and $u \in C^2(H^2(\mathbb{R}^d), [0, T])$ (i.e. $u(t, \bullet) \in H^2(\mathbb{R}^d)$ and $t \mapsto u(t, \bullet)$ continuous).

7.5 Propagation of the wave

Theorem 7.6 Assume that $u \in C^2(\mathbb{R}^d \times [0, \infty))$ and

$$\begin{cases} \partial_t^2 u - \Delta_x u = 0 & \mathbb{R}^d \times (0, \infty) \\ u = 0, \partial_t u = 0 & B(x_0, t_0) \times \{t = 0\} \end{cases}$$

Then $u(x, t) = 0$ for $x \in B(x_0, t_0 - t)$.

Proof. Let for $t \in [0, t_0]$

$$e(t) = \int_{B(x_0, t_0 - t)} (|\partial_t u|^2 + |\nabla_x u|^2) dx$$

■

This implies

$$\begin{aligned}
e'(t) &= \int_{B(x_0, t_0-t)} 2(\partial_t u \partial_t^2 u + \nabla_x u \partial_t \nabla_x u) - \int_{\partial B(x_0, t_0-t)} (|\partial_t u|^2 + |\nabla_x u|^2) dS \\
&= \int_{B(x_0, t_0-t)} 2(\partial_t u \partial_t^2 u - \Delta_x u \partial_t u) + \int_{\partial B(x_0, t_0-t)} [2(\nabla_x u \vec{n}) \partial_t u - |\partial_t u|^2 - |\nabla_x u|^2] dS \\
&= \int_{B(x_0, t_0-t)} 2(\partial_t u \underbrace{(\partial_t^2 u - \Delta_x u)}_{=0}) + \int_{\partial B(x_0, t_0-t)} \underbrace{[2(\nabla_x u \vec{n}) \partial_t u - |\partial_t u|^2 - |\nabla_x u|^2]}_{\leq 0} dS
\end{aligned}$$

where we used

$$|2(\nabla_x u \vec{n}) \partial_t u| \leq 2|\nabla_x u| |\partial_t u| \leq |\nabla_x u|^2 + |\partial_t u|^2.$$

Thus $e'(t) \leq 0$ for all $t \in (0, t_0)$, so $e(t) \leq e(0) = 0$ (as $u = 0$, $\partial_t u = 0$ in $B(x_0, t_0) \times \{t = 0\}$). This implies $e(t) = 0$ for all $t \in (0, t_0)$, so

$$\begin{cases} \partial_t u = 0 & x \in B(x_0, t_0 - t) \\ u = 0 & x \in B(x_0, t_0 - t) \times \{t = 0\} \end{cases}.$$

So we get that $u = 0$ for $x \in B(x_0, t_0 - t)$ for all $t \in (0, t_0)$ and $u = 0$ for $x \in B(x_0, t_0 - t)$ for all $t \in [0, t_0]$. (More precisely $u(x_0, t_0) = 0$)

7.6 Wave vs. Heat Equation

Notation 7.7 For $g \in L^2(\mathbb{R}^d)$, $t > 0$ we write $e^{t\Delta}g \in L^2(\mathbb{R}^d)$ for

$$\begin{aligned}
\widehat{e^{t\Delta}g}(k) &= e^{-t|2\pi k|^2} \hat{g}(k) \\
\Leftrightarrow (e^{t\Delta}g)(x) &= \frac{1}{(4\pi t)^{\frac{d}{2}}} \int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{4t}} g(y) dy \\
\frac{1}{(4\pi t)^{\frac{d}{2}}} e^{-\frac{|x|^2}{4t}} &= e^{-t|2\pi k|^2}
\end{aligned}$$

Heat Equation:

- Improves smoothness, *i.e.* $g \in L^2(\mathbb{R})$ implies $e^{t\Delta}g \in \bigcap_{m \geq 1} H^m(\mathbb{R}^d) \subseteq C^\infty(\mathbb{R}^d)$ for all $t > 0$.

- Propagation: Speed is ∞ .

$$t = 0: g \in C_c^\infty$$

$t > 0$: $e^{t\Delta}g$ does not have compact support

Wave Equation:

- No improvement of smoothness
- Propagation: Speed is finite

Chapter 8

Schrödinger Equation

$$\begin{cases} -i\partial_t u - \Delta_x u = 0 & \text{in } \mathbb{R}^d \times (0, \infty) \\ u(x, 0) = g(x) & x \in \mathbb{R}^d \end{cases}$$

Formally $-i\partial_t = \frac{1}{i} \frac{d}{dt} = \frac{d}{d(it)} \Rightarrow \partial_\xi u - \Delta_x u = 0$, $\xi = it \rightsquigarrow$ Heat equation with *imaginary time*. From the heat equation

$$\begin{aligned} \begin{cases} \partial_t u - \Delta_x u = 0 \\ u(x, 0) = g(x) \end{cases} &\Rightarrow u(x, t) = (e^{t\Delta} g)(x) = \frac{1}{(4\pi t)^{\frac{d}{2}}} \int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{4t}} g(y) dy \\ \rightsquigarrow \begin{cases} -i\partial_t u - \Delta_x u = 0 \\ u(x, 0) = g(x) \end{cases} &\Rightarrow u(x, t) = (e^{it\Delta} g)(x) = \frac{1}{(4\pi it)^{\frac{d}{2}}} \int_{\mathbb{R}^d} e^{i\frac{|x-y|^2}{4t}} g(y) dy \end{aligned}$$

if $g \in L^1$.

Theorem 8.1 For $g \in L^1(\mathbb{R}^d) \cap L^2(\mathbb{R}^d)$, define

$$(e^{it\Delta} g)(x) = \frac{1}{(4\pi it)^{\frac{d}{2}}} \int_{\mathbb{R}^d} e^{i\frac{|x-y|^2}{4t}} g(y) dy$$

Then $\|e^{it\Delta} g\|_{L^2(\mathbb{R}^d)} = \|g\|_{L^2(\mathbb{R}^d)}$. Consequently, for all $g \in L^2(\mathbb{R}^d)$ we can define $e^{it\Delta} g \in L^2(\mathbb{R}^d)$ by a density argument. Moreover,

$$\widehat{e^{it\Delta} g}(k) = e^{-it|2\pi k|^2} \hat{g}(k)$$

for almost every $k \in \mathbb{R}^d$.

Proof. Fourier transform of Gaussian:

$$\frac{1}{(4\pi t)^{\frac{d}{2}}} \widehat{e^{-\frac{|x|^2}{4t}}}(k) = e^{-t|2\pi k|^2}, \quad t > 0$$

Key point: This formula also holds if $t \in \mathbb{C}$ and $\Re(t) > 0$. For all $\epsilon > 0$ consider

$$(e^{(it+\epsilon)\Delta} g)(x) = \left(e^{-(it+\epsilon)|2\pi k|^2} \hat{g}(k) \right)^\vee(x) = (\hat{G}_\epsilon g)^\vee = (G_\epsilon \star g)(x)$$

where

$$G_\epsilon(x) = \frac{1}{(4\pi(it+\epsilon))^{\frac{d}{2}}} e^{-\frac{|x|^2}{4(it+\epsilon)}}.$$

Since $g \in L^1(\mathbb{R}^d)$:

$$\begin{aligned} (G_\epsilon \star g)(x) &= \frac{1}{(4\pi(it + \epsilon))^{\frac{d}{2}}} \int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{4(it+\epsilon)}} g(y) dy \\ &\longrightarrow \frac{1}{(4\pi it)^{\frac{d}{2}}} \int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{4it}} g(y) dy = (e^{it\Delta} g)(x) \end{aligned}$$

for all $x \in \mathbb{R}^d$. Moreover,

$$\begin{aligned} \|G_\epsilon \star g\|_{L^2(\mathbb{R}^d)} &= \|\widehat{G_\epsilon \star g}\|_{L^2(\mathbb{R}^d)} = \|\hat{G}_\epsilon \hat{g}\|_{L^2(\mathbb{R}^d)} = \left(\int_{\mathbb{R}^d} \left| e^{-(it+\epsilon)|2\pi k|^2} \right|^2 |\hat{g}(k)|^2 dk \right)^{\frac{1}{2}} \\ &= \left(\int_{\mathbb{R}^d} e^{-\epsilon|2\pi k|^2} |\hat{g}(k)|^2 dk \right)^{\frac{1}{2}} \xrightarrow{\epsilon \rightarrow 0^+} \left(\int_{\mathbb{R}^d} |\hat{g}(k)|^2 dk \right)^{\frac{1}{2}} = \|g\|_{L^2(\mathbb{R}^d)} \end{aligned}$$

as $g \in L^2(\mathbb{R}^d)$. Thus, $G_\epsilon \star g \rightarrow e^{it\Delta} g$ pointwise. With Fatou:

$$\liminf_{\epsilon \rightarrow 0^+} \|G_\epsilon \star g\|_{L^2(\mathbb{R}^d)} \geq \|e^{it\Delta} g\|_{L^2(\mathbb{R}^d)}$$

Thus, $e^{it\Delta} g \in L^2(\mathbb{R}^d)$ and $\|e^{it\Delta} g\|_{L^2(\mathbb{R}^d)} \leq \|g\|_{L^2(\mathbb{R}^d)}$. To get the equality:

$$\widehat{G_\epsilon \star g}(k) = e^{-(it+\epsilon)|2\pi k|^2} \underbrace{\hat{g}(k)}_{L^2} = \underbrace{e^{-\epsilon|2\pi k|^2}}_{\in[0,1]} \left(e^{-it|2\pi k|^2} \hat{g}(k) \right) \xrightarrow{\epsilon \rightarrow 0^+} e^{it|2\pi k|^2} \hat{g}(k)$$

in $L^2(\mathbb{R}^d, dk)$. Thus $G_\epsilon \star g$ converges in $L^2(\mathbb{R}^d)$. Then up to a subsequence $\epsilon \rightarrow 0^+$, we can assume that

$$(G_\epsilon \star g)(x) \xrightarrow{\epsilon \rightarrow 0^+} H(x)$$

almost everywhere. (Dominated convergence) We already proved $G_\epsilon \star g \rightarrow e^{it\Delta} g$ pointwise, so $e^{it\Delta} g = H$, i.e. $G_\epsilon \star g \rightarrow e^{it\Delta} g$ in $L^2(\mathbb{R}^d)$. Conclude

$$\|g\|_{L^2(\mathbb{R}^d)} \xleftarrow{\epsilon \rightarrow 0} \|G_\epsilon \star g\|_{L^2(\mathbb{R}^d)} \xrightarrow{\epsilon \rightarrow 0^+} \|e^{it\Delta} g\|_{L^2}.$$

This implies $\|e^{it\Delta} g\|_{L^2(\mathbb{R}^d)} = \|g\|_{L^2(\mathbb{R}^d)}$ for all $g \in L^1(\mathbb{R}^d) \cap L^2(\mathbb{R}^d)$. For $g \in L^2(\mathbb{R}^d)$ there is a sequence $\{g_n\} \subseteq L^1 \cap L^2$ s.t. $g_n \rightarrow g$ in $L^2(\mathbb{R}^d)$. Then

$$\|e^{it\Delta} g_n - e^{it\Delta} g_m\|_{L^2} = \|e^{it\Delta} \underbrace{(g_n - g_m)}_{L^1 \cap L^2}\|_{L^2} = \|g_n - g_m\|_{L^2} \rightarrow 0$$

as $m, n \rightarrow \infty$. So $e^{it\Delta} g_n$ is a Cauchy sequence in L^2 , so it has a limit which we define as $e^{it\Delta} g$. Why the limit $e^{it\Delta} g$ is independent of the choice of g_n : If we have 2 different sequences $\{g_n\}, \{\tilde{g}_n\} \subseteq L^1 \cap L^2$, then $g_n, \tilde{g}_n \rightarrow g$ in $L^2(\mathbb{R}^d)$. Then

$$\|e^{it\Delta} g_n - e^{it\Delta} \tilde{g}_n\|_{L^2(\mathbb{R}^d)} = \|e^{it\Delta} \underbrace{(g_n - \tilde{g}_n)}_{L^1 \cap L^2}\|_{L^2} = \|g_n - \tilde{g}_n\|_{L^2} \xrightarrow{n \rightarrow \infty} 0$$

$\leadsto \lim_{n \rightarrow \infty} e^{it\Delta} g_n = \lim_{n \rightarrow \infty} e^{it\Delta} \tilde{g}_n$. Finally, we have $g \in L^2(\mathbb{R}^d), g_n \in L^1 \cap L^2 \rightarrow g$ in L^2 .

$$\widehat{e^{it\Delta} g}(k) \xleftarrow{n \rightarrow \infty} \widehat{e^{it\Delta} g_n}(k) = e^{-it|2\pi k|^2} \hat{g}_n(k) \xrightarrow{n \rightarrow \infty} e^{-it|2\pi k|^2} \hat{g}(k)$$

in $L^2(\mathbb{R}^d)$. ■

Remark 8.2 (Long Term behavior)

1. If $g \in L^1(\mathbb{R}^d)$, then $(e^{it\Delta}g)(x) = \frac{1}{(4\pi it)^{\frac{d}{2}}} \int_{\mathbb{R}^d} e^{i\frac{|x-y|^2}{4t}} g(y) dy$. This implies

$$\|e^{it\Delta}g\|_{L^\infty} \leq \frac{1}{(4\pi t)^{\frac{d}{2}}} \|g\|_{L^1} \rightarrow 0$$

as $t \rightarrow \infty$. On the other hand, for all $g \in L^2(\mathbb{R}^d)$, $\|e^{it\Delta}g\|_{L^2} = \|g\|_{L^2}$.

Exercise: If $g \in L^1 \cap L^2$ then $\|e^{it\Delta}g\|_{L^p} \rightarrow 0$ for all $2 < p \leq \infty$.

2. For all bounded sets Ω , for all $g \in L^2(\mathbb{R}^d)$ we have $\|\mathbb{1}_\Omega e^{it\Delta}g\|_{L^2(\mathbb{R}^d)} \rightarrow 0$ as $t \rightarrow \infty$. Equivalently, for all $R > 0$:

$$\int_{|x| \leq R} |(e^{it\Delta}g)(x)|^2 dx \xrightarrow{t \rightarrow \infty} 0$$

(RAGE theorem)