Weighted Poincaré-Sobolev inequalities via fractional integration

12th International Conference on Harmonic Analysis and Partial Differential Equations

Alejandro Claros

BCAM - Basque Center for Applied Mathematics

El Escorial, June 12, 2025

Poincaré-Sobolev inequalities

Theorem (Poincaré-Sobolev Inequality)

Let $n \geq 2$ and $1 \leq p < n$. There exist a constant $c_{n,p} > 0$ such that for all ball $B \subset \mathbb{R}^n$ and all function $f \in W^{1,p}(B)$, the following inequality holds

$$\left(\frac{1}{|B|} \int_B |f(x) - f_B|^{p^*} \, dx \right)^{\frac{1}{p^*}} \leq c_{n,p} r(B) \left(\frac{1}{|B|} \int_B |\nabla f(x)|^p \, dx \right)^{\frac{1}{p}},$$

where $f_B = \frac{1}{|B|} \int_B f$ and $p^* = \frac{np}{n-p}$ $(\frac{1}{p} - \frac{1}{p^*} = \frac{1}{n})$.

Definition (Riesz potential)

The Riesz potential of a function $f : \mathbb{R}^n \longrightarrow \mathbb{R}$ is defined by

$$I_\alpha f(x) = \int_{\mathbb{R}^n} \frac{f(y)}{|x-y|^{n-\alpha}}\, dy,$$

for each $x \in \mathbb{R}^n$, where $\alpha \in (0, n)$.

Definition (Riesz potential)

The Riesz potential of a function $f:\mathbb{R}^n \longrightarrow \mathbb{R}$ is defined by

$$I_\alpha f(x) = \int_{\mathbb{R}^n} \frac{f(y)}{|x-y|^{n-\alpha}}\, dy,$$

for each $x \in \mathbb{R}^n$, where $\alpha \in (0,n)$.

- $I_\alpha : L^p(\mathbb{R}^n) \longrightarrow L^q(\mathbb{R}^n)$ for $1 < p < \frac{n}{\alpha}$ where $q = \frac{np}{n-\alpha p}$ $\left(\frac{1}{p} - \frac{1}{q} = \frac{\alpha}{n}\right)$.
- $I_\alpha : L^p(\mathbb{R}^n) \longrightarrow L^{q,\infty}(\mathbb{R}^n)$ for $1 \leq p < \frac{n}{\alpha}$.

Definition (Riesz potential)

The Riesz potential of a function $f:\mathbb{R}^n \longrightarrow \mathbb{R}$ is defined by

$$I_\alpha f(x) = \int_{\mathbb{R}^n} \frac{f(y)}{|x-y|^{n-\alpha}}\, dy,$$

for each $x \in \mathbb{R}^n$, where $\alpha \in (0,n)$.

- $I_\alpha : L^p(\mathbb{R}^n) \longrightarrow L^q(\mathbb{R}^n)$ for $1 < p < \frac{n}{\alpha}$ where $q = \frac{np}{n-\alpha p}$ $\left(\frac{1}{p} - \frac{1}{q} = \frac{\alpha}{n}\right)$.
- $I_\alpha : L^p(\mathbb{R}^n) \longrightarrow L^{q,\infty}(\mathbb{R}^n)$ for $1 \le p < \frac{n}{\alpha}$.

Theorem (Subrepresentation formula)

There exists $c_n > 0$ such that for each ball B,

$$|f(x) - f_B| \le c_n I_1(|\nabla f|\chi_B)(x), \qquad x \in B.$$

Poincaré-Sobolev inequalities

Proof.

Let $1 \leq p < n$,

$$\begin{aligned}\left\| f - f_B \right\|_{L^{p^*,\infty}(B,\frac{dx}{|B|})} &\leq c_n \left\| I_1(|\nabla f|\chi_B) \right\|_{L^{p^*,\infty}(B,\frac{dx}{|B|})} \\ &= c_n \frac{r(B)}{|B|^{\frac{1}{p}}} \left\| I_1(|\nabla f|\chi_B) \right\|_{L^{p^*,\infty}(B,dx)} \\ &\leq c_{n,p} r(B) \left(\frac{1}{|B|} \int_B |\nabla f(x)|^p dx \right)^{\frac{1}{p}}.\end{aligned}$$

Poincaré-Sobolev inequalities

Proof.

Let $1 \leq p < n$,

$$\begin{aligned}\left\| f - f_B \right\|_{L^{p^*,\infty}(B,\frac{dx}{|B|})} &\leq c_n \left\| I_1(|\nabla f|\chi_B) \right\|_{L^{p^*,\infty}(B,\frac{dx}{|B|})} \\ &= c_n \frac{r(B)}{|B|^{\frac{1}{p}}} \left\| I_1(|\nabla f|\chi_B) \right\|_{L^{p^*,\infty}(B,dx)} \\ &\leq c_{n,p} r(B) \left(\frac{1}{|B|} \int_B |\nabla f(x)|^p dx \right)^{\frac{1}{p}}.\end{aligned}$$

Using the **truncation method**, we obtain

$$\left(\frac{1}{|B|} \int_B |f(x) - f_B|^{p^*} dx \right)^{\frac{1}{p^*}} \leq C_{n,p} r(B) \left(\frac{1}{|B|} \int_B |\nabla f(x)|^p dx \right)^{\frac{1}{p}}.$$

□

Weighted Poincaré-Sobolev inequalities

Goal

To prove

$$\left(\frac{1}{w(B)}\int_B |f(x)-f_B|^{p_w^*} w(x)dx\right)^{\frac{1}{p_w^*}} \leq C_w r(B)\left(\frac{1}{w(B)}\int_B |\nabla f(x)|^p w(x)dx\right)^{\frac{1}{p}}$$

for an appropriate class of weights, where $p_w^* > p$.

Weighted Poincaré-Sobolev inequalities

Goal

To prove

$$\left(\frac{1}{w(B)}\int_B |f(x)-f_B|^{p_w^*} w(x)dx\right)^{\frac{1}{p_w^*}} \leq C_w r(B)\left(\frac{1}{w(B)}\int_B |\nabla f(x)|^p w(x)dx\right)^{\frac{1}{p}}$$

for an appropriate class of weights, where $p_w^* > p$.

Goal

Good bounds for C_w and p_w^*.

Motivation: Degenerate elliptic operators

$$Lu = \operatorname{div}(A(x) \cdot \nabla u), \qquad Lu = 0$$

$$c|\xi|^2 w(x) \leq A(x)\xi \cdot \xi \leq C|\xi|^2 w(x)$$

where w is a weight with some singularity.

Goal: To prove local Hölder continuity of the solutions of the equation.

Motivation: Degenerate elliptic operators

$$Lu = \operatorname{div}(A(x)\cdot\nabla u), \qquad Lu = 0$$

$$c|\xi|^2 w(x) \le A(x)\xi\cdot\xi \le C|\xi|^2 w(x)$$

where w is a weight with some singularity.
Goal: To prove local Hölder continuity of the solutions of the equation.

Moser iteration method: Fabes, Kenig, Serapioni (1982).
Let $w \in A_2$,

- Weighted Poincaré-Sobolev inequality:

$$\left(\frac{1}{w(B)}\int_B |f-f_B|^{2_w^*} w dx\right)^{\frac{1}{2_w^*}} \le C_w r(B)\left(\frac{1}{w(B)}\int_B |\nabla f|^2 w dx\right)^{\frac{1}{2}},$$

  where $2_w^* > 2$.

Fractional integrals and A_p weights

Motivated by the work of T. Alberico, A. Cianchi, and C. Sbordone (2009).

Theorem (C.)

Let $n \geq 1$, $\alpha \in (0,n)$ and $1 < p < \frac{n}{\alpha}$. Let $w \in A_r$ with $1 \leq r \leq p$. Consider q_r defined by the relation

$$\frac{1}{p} - \frac{1}{q_r} = \frac{\alpha}{n} \frac{\tau_n [\sigma]_{A_\infty}}{1 + r(\tau_n [\sigma]_{A_\infty} - 1)},$$

where $\sigma = w^{1-r'}$ and $\tau_n = 2^{n+1}$ if $r > 1$ and $q_1 = p_\alpha^* = \frac{np}{n - \alpha p}$. Then, there exists a constant $C > 0$ such that

$$\left(\frac{1}{w(B)} \int_B |I_\alpha f(x)|^{q_r} w(x) dx \right)^{\frac{1}{q_r}} \leq C \frac{p_\alpha^*}{\alpha} [w]_{A_r}^{\frac{1}{p}} [\sigma]_{A_\infty}^{\frac{1}{q_r}} r(B)^\alpha \left(\frac{1}{w(B)} \int_B |f(x)|^p w(x) dx \right)^{\frac{1}{p}},$$

for any ball $B \subset \mathbb{R}^n$ and every function $f \in L^p(B, w)$.

Fractional integrals and A_p weights

Theorem (C.)

Let $n \geq 1$, $\alpha \in (0,n)$ and $1 \leq p < \frac{n}{\alpha}$. Let $w \in A_r$ with $1 \leq r \leq p$. Consider q_r defined by the relation

$$\frac{1}{p} - \frac{1}{q_r} = \frac{\alpha}{n} \frac{\tau_n [\sigma]_{A_\infty}}{1 + r(\tau_n [\sigma]_{A_\infty} - 1)},$$

where $\sigma = w^{1-r'}$ if $r > 1$ and $q_1 = p_\alpha^* = \frac{np}{n - \alpha p}$. Then, there exists a dimensional constant $c_n > 0$ such that

$$\left\| I_\alpha f \right\|_{L^{q_r,\infty}\left(B, \frac{w(x)dx}{w(B)}\right)} \leq \frac{c_n}{\alpha} p_\alpha^* [w]_{A_r}^{\frac{1}{p}} r(B)^\alpha \left(\frac{1}{w(B)} \int_B |f(x)|^p w(x) dx \right)^{\frac{1}{p}},$$

for any ball $B \subset \mathbb{R}^n$ and every function $f \in L^p(B,w)$.

Weighted Hedberg's inequality

Lemma (C.)

Let $n \geq 1$, $\alpha \in (0, n)$, let $1 < p < \frac{n}{\alpha}$ and let w be a weight. Let $1 < r \leq p$ and consider q defined by the relation

$$\frac{1}{p} - \frac{1}{q} = \frac{\alpha}{n} \frac{1}{r}.$$

Then, there exists a dimensional constant $c_n > 0$ such that for any ball B such that $0 < \int_B w(y)^{1-r'} dy < \infty$ and every function $f \in L^p(B, w)$, we have

$$|I_\alpha f(x)| \leq \frac{c_n}{\alpha} p_\alpha^* M f(x)^{\frac{p}{q}} \|f\|_{L^p(B,w)}^{1-\frac{p}{q}} \left(\int_B w(y)^{1-r'} dy \right)^{\frac{\alpha}{nr'}},$$

for any $x \in B$.

Applications to Poincaré-Sobolev inequalities

Theorem (C.)

Let $n \geq 2$ and let $1 \leq p < n$. Let $w \in A_r$ for some $1 \leq r \leq p$ and consider q_r defined by the relation

$$\frac{1}{p} - \frac{1}{q_r} = \frac{1}{n} \frac{\tau_n [\sigma]_{A_\infty}}{1 + r(\tau_n [\sigma]_{A_\infty} - 1)}$$

where $\sigma = w^{1-r'}$ if $r > 1$ and $q_1 = p^* = \frac{np}{n-p}$. Then, there exists a dimensional constant $c_n > 0$ such that,

$$\left(\frac{1}{w(B)} \int_B |f(x) - f_B|^{q_r} w(x) dx \right)^{\frac{1}{q_r}} \leq c_n p^* [w]_{A_r}^{\frac{1}{p}} r(B) \left(\frac{1}{w(B)} \int_B |\nabla f(x)|^p w(x) dx \right)^{\frac{1}{p}}$$

for any ball B, and the exponent $\frac{1}{p}$ on the A_r constant is ***sharp****.*

Applications to Poincaré-Sobolev inequalities

Theorem (C.)

Let $n \geq 2$ and let $1 \leq p < n$. Let $w \in A_r$ for some $1 \leq r \leq p$ and consider q_r defined by the relation

$$\frac{1}{p} - \frac{1}{q_r} = \frac{1}{n} \frac{\tau_n [\sigma]_{A_\infty}}{1 + r(\tau_n [\sigma]_{A_\infty} - 1)}$$

where $\sigma = w^{1-r'}$ if $r > 1$ and $q_1 = p^* = \frac{np}{n-p}$. Then, there exists a dimensional constant $c_n > 0$ such that,

$$\left(\frac{1}{w(B)} \int_B |f(x) - f_B|^{q_r} w(x) dx \right)^{\frac{1}{q_r}} \leq c_n p^* [w]_{A_r}^{\frac{1}{p}} r(B) \left(\frac{1}{w(B)} \int_B |\nabla f(x)|^p w(x) dx \right)^{\frac{1}{p}}$$

for any ball B, and the exponent $\frac{1}{p}$ on the A_r constant is ***sharp****.*

- The case $r = 1$ ($w \in A_1$) of the theorem answers positively to a conjecture of Pérez-Rela (2019) about the sharp exponent in the A_1 constant.

Applications to Fractional Poincaré-Sobolev inequalities

- Let $1 \leq p < \infty$ and let $\delta \in (0,1)$. Then, for all ball $B \subset \mathbb{R}^n$ and all function $f \in W^{\delta,p}(B)$, the following inequality holds

$$\frac{1}{|B|}\int_B |f(x) - f_B| dx \leq c_n r(B)^{\delta} \left(\frac{1}{|B|} \int_B \int_B \frac{|f(x)-f(y)|^p}{|x-y|^{n+\delta p}} dy\, dx \right)^{\frac{1}{p}}.$$

Applications to Fractional Poincaré-Sobolev inequalities

- Let $1 \leq p < \infty$ and let $\delta \in (0,1)$. Then, for all ball $B \subset \mathbb{R}^n$ and all function $f \in W^{\delta,p}(B)$, the following inequality holds

$$\frac{1}{|B|}\int_B |f(x) - f_B| dx \leq c_n r(B)^{\delta} \left(\frac{1}{|B|}\int_B \int_B \frac{|f(x)-f(y)|^p}{|x-y|^{n+\delta p}} dy\, dx \right)^{\frac{1}{p}}.$$

- Bourgain-Brezis-Mironescu (2001)

$$\lim_{\delta \uparrow 1} (1-\delta)^{\frac{1}{p}} \left(\int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|f(x)-f(y)|^p}{|x-y|^{n+\delta p}} dy\, dx \right)^{\frac{1}{p}} = K_{n,p} \left(\int_{\mathbb{R}^n} |\nabla f(x)|^p dx \right)^{\frac{1}{p}}.$$

Applications to Fractional Poincaré-Sobolev inequalities

- Let $1 \leq p < \infty$ and let $\delta \in (0,1)$. Then, for all ball $B \subset \mathbb{R}^n$ and all function $f \in W^{\delta,p}(B)$, the following inequality holds

$$\frac{1}{|B|}\int_B |f(x) - f_B| dx \leq c_n r(B)^{\delta} \left(\frac{1}{|B|}\int_B \int_B \frac{|f(x)-f(y)|^p}{|x-y|^{n+\delta p}} dy\, dx \right)^{\frac{1}{p}}.$$

- Bourgain-Brezis-Mironescu (2001)

$$\lim_{\delta \uparrow 1} (1-\delta)^{\frac{1}{p}} \left(\int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|f(x)-f(y)|^p}{|x-y|^{n+\delta p}} dy\, dx \right)^{\frac{1}{p}} = K_{n,p} \left(\int_{\mathbb{R}^n} |\nabla f(x)|^p dx \right)^{\frac{1}{p}}.$$

- Bourgain-Brezis-Mironescu (2001), Milman (2005)

$$\frac{1}{|B|}\int_B |f(x) - f_B| dx \leq c_n (1-\delta)^{\frac{1}{p}} r(B)^{\delta} \left(\frac{1}{|B|}\int_B \int_B \frac{|f(x)-f(y)|^p}{|x-y|^{n+\delta p}} dy\, dx \right)^{\frac{1}{p}}.$$

Applications to Fractional Poincaré-Sobolev inequalities

Theorem (C.)

Let $n \geq 2$, $\delta \in (0,1)$, $1 \leq p < \frac{n}{\delta}$ and let $w \in A_1$. Then, there exists a dimensional constant $c_n > 0$ such that,

$$\left(\frac{1}{w(B)}\int_B |f(x)-f_B|^{p\left(\frac{n}{\delta}\right)'} w(x)dx\right)^{\frac{1}{p\left(\frac{n}{\delta}\right)'}} \leq c_n(1-\delta)^{\frac{1}{p}}[w]_{A_1}^{\frac{1}{p}} r(B)^{\delta} \cdot \left(\frac{1}{w(B)}\int_B\int_B \frac{|f(x)-f(y)|^p}{|x-y|^{n+\delta p}}dy\, w(x)dx\right)^{\frac{1}{p}}$$

for any ball B.

Weighted Sobolev exponent

Definition

Let $w \in A_\infty$, we define

$$I(w) := \{p \geq 1 : w \in A_p\}$$

Weighted Sobolev exponent

Definition

Let $w \in A_\infty$, we define

$$I(w) := \{p \geq 1 : w \in A_p\} = \begin{cases} [1, \infty) & \text{if } w \in A_1 \end{cases}$$

Weighted Sobolev exponent

Definition

Let $w \in A_\infty$, we define

$$I(w) := \{p \geq 1 : w \in A_p\} = \begin{cases} [1, \infty) & \text{if } w \in A_1 \\ (\ell_w, \infty) & \text{if } w \in A_\infty \setminus A_1 \end{cases},$$

where $\ell_w := \inf I(w)$.

Weighted Sobolev exponent

Definition

Let $w \in A_\infty$, we define

$$I(w) := \{p \geq 1 : w \in A_p\} = \begin{cases} [1,\infty) & \text{if } w \in A_1 \\ (\ell_w,\infty) & \text{if } w \in A_\infty \setminus A_1 \end{cases},$$

where $\ell_w := \inf I(w)$.

Definition

Let $n \geq 2$, $1 \leq p < n$ and let $w \in A_\infty$. We define the weighted Sobolev exponent p_w^* by the relation

$$\frac{1}{p} - \frac{1}{p_w^*} = \frac{1}{n}\frac{1}{\ell_w}.$$

Weighted Sobolev exponent

Corollary (C.)

Let $1 \le p < n\ell_w$ and let $w \in A_p$. Then, for each $1 \le q < p^*_w$, we have

$$\left(\frac{1}{w(B)}\int_B |f(x)-f_B|^q w(x)dx\right)^{\frac{1}{q}} \le C_w r(B)\left(\frac{1}{w(B)}\int_B |\nabla f(x)|^p w(x)dx\right)^{\frac{1}{p}}$$

for any ball B, where C_w is of the form $c_n p^* [w]_{A_r}^{\frac{1}{p}}$ for some $r = r(q) > \ell_w$.

Weighted Sobolev exponent

Corollary (C.)

Let $1 \le p < n\ell_w$ and let $w \in A_p$. Then, for each $1 \le q < p_w^*$, we have

$$\left(\frac{1}{w(B)}\int_B |f(x)-f_B|^q w(x)dx\right)^{\frac{1}{q}} \le C_w r(B)\left(\frac{1}{w(B)}\int_B |\nabla f(x)|^p w(x)dx\right)^{\frac{1}{p}}$$

for any ball B, where C_w is of the form $c_n p^* [w]_{A_r}^{\frac{1}{p}}$ for some $r = r(q) > \ell_w$.

Theorem (C.)

We can find a weight $w \in A_p$ such that if the inequality

$$\left(\frac{1}{w(B)}\int_B |f(x)-f_B|^q w(x)dx\right)^{\frac{1}{q}} \le C_w r(B)\left(\frac{1}{w(B)}\int_B |\nabla f(x)|^p w(x)dx\right)^{\frac{1}{p}}$$

holds for all Lipschitz function f, then $q \le p_w^*$.

Weighted Sobolev exponent

Corollary (C.)

Let $1 \le p < n\ell_w$ and let $w \in A_p$. Then, for each $1 \le q < p_w^*$, we have

$$\left(\frac{1}{w(B)}\int_B |f(x)-f_B|^q w(x)dx\right)^{\frac{1}{q}} \le C_w r(B)\left(\frac{1}{w(B)}\int_B |\nabla f(x)|^p w(x)dx\right)^{\frac{1}{p}}$$

for any ball B, where C_w is of the form $c_n p^* [w]_{A_r}^{\frac{1}{p}}$ for some $r = r(q) > \ell_w$.

Theorem (C.)

We can find a weight $w \in A_p$ such that if the inequality

$$\left(\frac{1}{w(B)}\int_B |f(x)-f_B|^q w(x)dx\right)^{\frac{1}{q}} \le C_w r(B)\left(\frac{1}{w(B)}\int_B |\nabla f(x)|^p w(x)dx\right)^{\frac{1}{p}}$$

holds for all Lipschitz function f, then $q \le p_w^*$.

- We do **not** know if the inequality holds at the endpoint $q = p_w^*$.

¡Gracias!