FRACTIONAL SOBOLEV-POINCARÉ INEQUALITIES IN IRREGULAR DOMAINS

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Abstract. This paper is devoted to the study of fractional \((q, p)\)-Sobolev-Poincaré inequalities in irregular domains. In particular, we establish (essentially) sharp fractional \((q, p)\)-Sobolev-Poincaré inequality in \(s\)-John domains and in domains satisfying the quasihyperbolic boundary conditions. When the order of the fractional derivative tends to 1, our results tend to the results for the usual derivative. Furthermore, we verified that those domains that support the fractional\((q, p)\)-Sobolev-Poincaré inequality together with a separation property are \(s\)-diam John domains for certain \(s\), depending only on the associated data. We also point out an inaccurate statement in [2].

Introduction

Recall that a bounded domain \(\Omega \subset \mathbb{R}^n\) is a John domain if there is a constant \(C\) and a point \(x_0 \in \Omega\) so that, for each \(x \in \Omega\), one can find a rectifiable curve \(\gamma : [0, 1] \to \Omega\) with \(\gamma(0) = x\), \(\gamma(1) = x_0\) and with
\[
Cd(\gamma(t), \partial \Omega) \geq l(\gamma([0, t]))
\]
for each \(0 < t \leq 1\). F. John used this condition in his work on elasticity [11] and the term was coined by Martio and Sarvas [14]. Smith and Stegenga [16] introduced the more general concept of \(s\)-John domains, \(s \geq 1\), by replacing (1.1) with
\[
Cd(\gamma(t), \partial \Omega) \geq l(\gamma([0, t]))^s.
\]
The condition (1.1) is called a “twisted cone condition” in literature. Thus condition (1.2) should be called a “twisted cusp condition”.

In the last twenty years, \(s\)-John domains has been extensively studied in connection with Sobolev type inequalities; see [2, 4, 8, 12, 13, 16]. In particular, Buckley and Koskela [2] have shown that a simply connected planar domain which supports a Sobolev-Poincaré inequality is an \(s\)-John domain for an appropriate \(s\). Smith and Stegenga have shown that an \(s\)-John domain \(\Omega\) is a \(p\)-Poincaré domain, provided \(s < \frac{n}{n-1} + \frac{1}{p-1}\). In particular, if \(s < \frac{n}{n-1}\), then \(\Omega\) is a \(p\)-Poincaré domain for all \(1 \leq p < \infty\). These results were further generalized to the case of \((q, p)\)-Poincaré domains in [8, 12, 13]. Recall that a bounded domain \(\Omega \subset \mathbb{R}^n\), \(n \geq 2\), is said to be a \((q, p)\)-Poincaré domain if there exists a constant \(C_{q, p} = C_{q, p}(\Omega)\) such that
\[
\left( \int_\Omega |u(x) - u_\Omega|^q dx \right)^{1/q} \leq C_{q, p} \left( \int_\Omega |\nabla u(x)|^p dx \right)^{1/p}
\]
for all $u \in C^\infty(\Omega)$. Here $u_\Omega = \frac{1}{|\Omega|} \int_\Omega u(x)dx$. When $q = p$, $\Omega$ is termed a $p$-Poincaré domain and when $q > p$ we say that $\Omega$ supports a Sobolev-Poincaré inequality.

In this paper, we consider the following fractional $(q,p)$-Sobolev-Poincaré inequality in a domain $\Omega \subset \mathbb{R}^n$ with finite Lebesgue measure, $n \geq 2$:

$$
(1.4) \quad \int_\Omega |u(x) - u_\Omega|^qdx \leq C \left( \int_{\Omega \cap B(x,\tau d(x,\partial \Omega))} \frac{|u(x) - u(y)|^p}{|x-y|^{|n + p\delta|}} dy \right)^{q/p},
$$

where $1 \leq p \leq q < \infty$, $\delta \in (0,1)$, $\tau \in (0,\infty)$ and the constant $C$ does not depend on $u \in C(\Omega)$. If $\Omega$ supports the fractional $(q,p)$-Sobolev-Poincaré inequality $(1.4)$, $q \geq p$, then we say that $\Omega$ is a fractional $(q,p)$-Sobolev-Poincaré domain.

From now on, unless specified, $\delta \in (0,1)$ and $\tau \in (0,\infty)$ will be fixed constants. Given a function $u \in C(\Omega)$, we define $g_u : \Omega \rightarrow \mathbb{R}$ as

$$
(1.5) \quad g_u(x) = \int_{\Omega \cap B(x,\tau d(x,\partial \Omega))} \frac{|u(x) - u(y)|^p}{|x-y|^{|n + p\delta|}} dy
$$

for $x \in \Omega$.

**Theorem 1.1.** Let $\Omega \subset \mathbb{R}^n$, $n \geq 2$, be a domain with finite Lebesgue measure and $1 \leq p \leq q < \infty$. Then the following statements are equivalent:

i) $\Omega$ satisfies the fractional $(q,p)$-Sobolev-Poincaré inequality;

ii) For an arbitrary ball $B_0 \subset \Omega$ there exists a constant $C = C(\Omega,p,q,B_0)$ such that

$$
(1.6) \quad |A|^{p/q} \leq C \inf_\Omega g_u(x)dx
$$

for every measurable set $A \subset \Omega$ such that $A \cap B_0 = \emptyset$. The infimum above is taken over all functions $u \in C(\Omega)$ that satisfy $u|_A \geq 1$ and $u|_{B_0} = 0$.

**Theorem 1.2.** Let $\Omega \subset \mathbb{R}^n$, $n \geq 2$, be an s-John domain. If $p < n/\delta$, $s < \frac{n}{n-p\delta}$ and $1 \leq p < q < \frac{np}{s(n-p\delta)+(s-1)(p-1)}$, then $\Omega$ supports the fractional $(q,p)$-Sobolev-Poincaré inequality $(1.4)$.

The range for $q$ in Theorem 1.2 is essentially sharp as indicated by the following example.

**Example 1.3.** Given $\tau, \delta \in (0,1)$, $1 \leq p < n/\delta$ and $s < \frac{n}{n-p\delta}$, there exists an s-John domain $\Omega \subset \mathbb{R}^n$ such that $\Omega$ does not support any fractional $(q,p)$-Sobolev-Poincaré inequality with $q > \frac{np}{s(n-p\delta)+(s-1)(p-1)}$.

Theorem 1.2 holds for the critical case $q = \frac{np}{s(n-p\delta)+(s-1)(p-1)}$ as well, provided $s = 1$ or $p = 1$; see Remark 4.1. We conjecture that Theorem 1.2 holds, under the same assumptions, for the critical case $q = \frac{np}{s(n-p\delta)+(s-1)(p-1)}$.

**Theorem 1.4.** Let $\Omega \subset \mathbb{R}^n$, $n \geq 2$, satisfy the quasihyperbolic boundary condition $(5.1)$ for some $\beta \leq 1$. Then $\Omega$ is a fractional $(q,p)$-Sobolev-Poincaré domain provided $p \in \left[ \frac{1}{2} \left( n - n \frac{2\beta}{1+\beta} \right), n \right)$ and $q \in \left[ p, \frac{np}{s(n-p\delta)+(s-1)(p-1)} \right]$.

**Example 1.5.** For each $q > \frac{2\beta np}{1+\beta n-p\delta}$, there exists a domain $\Omega \subset \mathbb{R}^n$, $n \geq 2$, satisfying $(5.1)$ which is not a fractional $(q,p)$-Sobolev-Poincaré domain. For each $1 \leq p < \frac{1}{2} \left( n - n \frac{2\beta}{1+\beta} \right)$, there exist domains $\Omega \subset \mathbb{R}^n$, $n \geq 2$, satisfying $(5.1)$ which is not a fractional $(p,p)$-Sobolev-Poincaré domain.
Recall that we say a domain \( \Omega \subset \mathbb{R}^n \) with a distinguished point \( x_0 \) has a separation property if there exists a constant \( C_0 \) such that the following property holds: for every \( x \in \Omega \), there exists a curve \( \gamma : [0,1] \to \Omega \) with \( \gamma(0) = x \), \( \gamma(1) = x_0 \), and such that for each \( t \) either
\[
\gamma([0,t]) \subset B_t := B(\gamma(t), C_0 d(\gamma(t), \partial \Omega))
\]
or each \( y \in \gamma([0,t]) \setminus B_t \) and \( x_0 \) belong to different components of \( \Omega \setminus \partial B_t \).

**Theorem 1.6.** Assume that \( \Omega \subset \mathbb{R}^n \) is a domain of finite Lebesgue measure that satisfies the separation property with a distinguished point \( x_0 \). Let \( 1 \leq p < \frac{n}{q} \). If \( \Omega \) is a fractional \((q,p)-\)Sobolev-Poincaré domain with \( \tau = 1 \) for some \( q > p \), then for each \( x \in \Omega \), there is curve \( \gamma : [0,1] \to \Omega \) with \( \gamma(0) = x \), \( \gamma(1) = x_0 \) such that
\[
\text{diam} \gamma([0,t]) \leq C \varphi(d(\gamma(t), \partial \Omega)),
\]
where \( \varphi(t) = t^{\frac{\alpha - npq}{pq}} (\frac{1}{p} - \frac{1}{q}) \).

The assumptions in Theorem 1.6 can be further relaxed. Indeed, Theorem 1.6 holds if we only assume that the fractional \((q,p)-\)Sobolev-Poincaré inequality (1.4) holds for all locally Lipschitz continuous functions in \( \Omega \); see Remark 3.4.

Since the paper generalizes the main results of [9, 13, 3, 2] to the fractional setting in a natural way, some of the arguments used in this paper are similar to ones in those papers. In particular, we benefit a lot from [9] and [13]. This paper is organized as follows. Section 2 contains the basic definitions and Section 3 some auxiliary results. We prove our main results, namely Theorem 1.1, Theorem 1.2 and Example 1.3 in Section 4. In Section 5, we prove Theorem 1.4 and give the construction of Example 1.5. In the final section, Section 6, we discuss the proof of Theorem 1.6 and point out a mistake in [2].

2. Notations and definitions

Recall that the quasihyperbolic metric \( k_\Omega \) in a domain \( \Omega \subset \mathbb{R}^n \) is defined to be
\[
k_\Omega(x,y) = \inf_\gamma k_\Omega - \text{length}(\gamma),
\]
where the infimum is taken over all rectifiable curves \( \gamma \) in \( \Omega \) which join \( x \) to \( y \) and
\[
k_\Omega - \text{length}(\gamma) = \int_\gamma \frac{ds}{d(x, \partial \Omega)}
\]
denotes the quasihyperbolic length of \( \gamma \) in \( \Omega \). This metric was introduced by Gehring and Palka in [5]. A curve \( \gamma \) joining \( x \) to \( y \) for which \( k_\Omega - \text{length}(\gamma) = k_\Omega(x,y) \) is called a quasihyperbolic geodesic. Quasihyperbolic geodesics joining any two points of a proper subdomain of \( \mathbb{R}^n \) always exists; see [4, Lemma 1].

Let \( \Omega \) be a bounded domain in \( \mathbb{R}^n \), \( n \geq 2 \). Then \( \mathcal{W} = \mathcal{W}(\Omega) \) denotes a Whitney decomposition of \( \Omega \), i.e. a collection of closed cubes \( Q \subset \Omega \) with pairwise disjoint interiors and having edges parallel to the coordinate axes, such that \( \Omega = \bigcup_{Q \in \mathcal{W}} Q \), the diameters of \( Q \in \mathcal{W} \) belong to the set \( \{2^{-j} : j \in \mathbb{Z}\} \) and satisfy the condition
\[
\text{diam}(Q) \leq \text{dist}(Q, \partial \Omega) \leq 4 \text{diam}(Q).
\]
For \( j \in \mathbb{Z} \) we define
\[
\mathcal{W}_j = \{ Q \in \mathcal{W} : \text{diam}(Q) = 2^{-j}\}.
\]

Note that when we write \( f(x) \lesssim g(x) \), we mean that \( f(x) \leq C g(x) \) is satisfied for all \( x \) with some fixed constant \( C \geq 1 \). Similarly, the expression \( f(x) \gtrsim g(x) \)
means that \( f(x) \geq C^{-1}g(x) \) is satisfied for all \( x \) with some fixed constant \( C \geq 1 \).
We write \( f(x) \approx g(x) \) whenever \( f(x) \gtrsim g(x) \) and \( f(x) \gtrsim g(x) \).

3. Auxiliary results

We need the following “chain lemma” from [7] Proof of Theorem 9.

**Lemma 3.1.** Let \( \Omega \subset \mathbb{R}^n \) be an \( s \)-John domain and \( M > 1 \) a fixed constant. Let \( B_0 = B(x_0, \frac{d(x_0, \partial \Omega)}{4M}) \), where \( x_0 \in \Omega \) is the John center. There exists a constant \( c > 0 \), depending only on \( \Omega \), \( M \) and \( n \), such that given \( x \in \Omega \), there exists a finite “chain” of balls \( B_i = B(x_i, r_i) \), \( i = 0, 1, \ldots, k \) (\( k \) depends on the choice of \( x \)) that joins \( x_0 \) to \( x \) with the following properties:

1. \( |B_i \cup B_{i+1}| \leq c|B_i \cap B_{i+1}| \);
2. \( d(x, B_i) \leq cr_i^{1/s} \);
3. \( d(B_i, \partial \Omega) \geq Mr_i \);
4. \( \sum_{i=0}^{k} \chi_{B_i} \leq c\chi_{\Omega} \);
5. \( |x - x_i| \leq cr_i^{1/s} \) and \( B_k = B(x, \frac{d(x, \partial \Omega)}{4M}) \);
6. For any \( r > 0 \), the number of balls \( B_i \) with radius \( r_i > r \) is less than \( cr^{(1-s)/s} \) when \( s > 1 \).

Recall that for a function \( f \), the Riesz potential \( I_\delta \), \( \delta \in (0, n) \), of \( f \) is defined by

\[
I_\delta(f) = \int_{\mathbb{R}^n} \frac{f(y)}{|x - y|^{n-\delta}} dy.
\]

The following estimate for Riesz potential is well-known; see for instance [1] Theorem 3.1.4 and Corollary 3.1.5.

**Theorem 3.2.** Let \( 0 < \delta < n, 1 < p < q < \infty \), and \( 1/p - 1/q = \delta/n \). Then \( \|I_\delta(f)\|_q \leq c\|f\|_p \) for some constant \( c \) independent of \( f \in L^p(\mathbb{R}^n) \). Moreover, there is a constant \( c_1 \) \( c(n, \delta) > 0 \) such that the weak estimate

\[
\sup_{t>0} \{x \in \mathbb{R}^n : |I_\delta(f)(x)| > t\}1^{n/(n-\delta)} \leq c_1 \|f\|_1^{n/(n-\delta)}
\]

holds for every \( f \in L^1(\mathbb{R}^n) \).

The following proposition, which can regarded as a fractional analogy of [2] Theorem 2.1, is proved in [3] Proposition 6.2.

**Proposition 3.3.** Suppose that \( \Omega \subset \mathbb{R}^n \) is a domain of finite Lebesgue measure. Let \( 1 \leq p < q < \infty \). Assume that the fractional \((q, p)\)-Sobolev-Poincaré inequality \((1.4)\) holds with \( r = 1 \) for every \( u \in C(\Omega) \). Fix a ball \( B_0 \subset \Omega \), and let \( d > 0 \) and \( w \in \Omega \). Then there exists a constant \( C > 0 \) such that

\[
\text{diam}(T) \leq C \left(d + |T|^\left(\frac{1}{q} - \frac{1}{p}\right)\right)
\]

and

\[
|T|^{1/n} \leq C(d + d^{(n-pq)/(np)})
\]

if \( T \) is the union of all components of \( \Omega \setminus B(w, d) \) that do not intersect the ball \( B_0 \). The constant \( C \) depends only on \( |B_0|, |\Omega|, n, p, q, \delta \) and the constant associated to the fractional \((q, p)\)-Sobolev-Poincaré inequality.
Remark 3.4. As in [2], one can check that the conclusion holds whenever the fractional \((q, p)\)-Sobolev-Poincaré inequality (1.4) with \(\tau = 1\) holds for every locally Lipschitz continuous functions; see [3, Proof of Proposition 6.2].

The following lemma is proved in [13, Lemma 2.6].

Lemma 3.5. Let \(\Omega \subset \mathbb{R}^n, n \geq 2\), be a domain that satisfies the quasihyperbolic boundary condition (5.1). Then for each \(\varepsilon > 0\) there exists a constant \(C = C(n, \text{diam } \Omega, \varepsilon)\) such that

\[
\sup_{Q_1 \in \mathcal{W}} \sum_{Q \in P(Q_1)} |Q|^\varepsilon \leq C. \tag{3.3}
\]

Fix a Whitney cube \(Q_0\) and assume that \(x_0\) is the center of \(Q_0\). For each cube \(Q \in \mathcal{W}\), we choose a quasihyperbolic geodesic \(\gamma\) joining \(x_0\) to the center of \(Q\) and we let \(P(Q)\) denote the collection of all the Whitney cubes \(Q' \in \mathcal{W}\) which intersect \(\gamma\). Then the shadow \(S(Q)\) of the cube \(Q\) is defined to be

\[
S(Q) = \bigcup_{Q_1 \in \mathcal{W}, Q \in P(Q_1)} Q_1.
\]

We need the following estimate of the size of the shadow of a Whitney cube \(Q\) in terms of the size of \(Q\). The proof is essentially contained in [13, Lemma 2.8] with minor modifications.

Lemma 3.6. Let \(\Omega \subset \mathbb{R}^n, n \geq 2\), be a domain that satisfies the quasihyperbolic boundary condition (5.1). Then there exists a constant \(C = C(n)\) such that

\[
\text{diam } S(Q) \leq C \left(\text{diam } Q\right)^{\frac{2\beta}{1+\beta}}
\]

for all \(Q \in \mathcal{W}\). Consequently,

\[
|S(Q)| \leq C |Q|^{\frac{2\beta}{1+\beta}}. \tag{3.4}
\]

4. Main proofs

Proof of Theorem 1.1. We first show that condition \(ii\) implies condition \(i\). Fix a function \(u \in C(\Omega)\). Pick a real number \(b\) such that both \(|\{x \in \Omega : u(x) \geq b\}|\) and \(|\{x \in \Omega : u(x) \leq b\}|\) are at least \(|\Omega|/2\). It suffices to show the fractional \((q, p)\)-Sobolev-Poincaré inequality with \(|u - u_Q|\) replaced by \(|u - b|\), and by replacing \(u\) with \(u - b\), we may assume that \(b = 0\). Write \(v_+ = \max\{u, 0\}\) and \(v_- = -\min\{u, 0\}\). In the sequel \(v\) denotes either \(v_+\) or \(v_-\); all the statements below are valid in both cases. Without loss of generality, we may assume that \(v \geq 0\).

For each \(j \in \mathbb{Z}\), we define \(v_j(x) = \min\{2^j, \max\{0, v(x) - 2^j\}\}\). We next prove the following inequality

\[
2^{nj}\{x \in \Omega : v_j(x) \geq 2^j\} \leq C \left(\int_\Omega g_{v_j}(x)dx\right)^{q/p}. \tag{4.1}
\]

To see it, notice that \(2^{-j}v_j|_{F_0} = 0\) and \(2^{-j}v_j|_{F_j} \geq 1\), where \(F_j = \{x \in \Omega : v_j(x) \geq 2^j\}\). So by (1.6), we obtain that

\[
|F_j|^{p/q} \leq C \int_{\Omega} g_{2^{-j}v_j}(x)dx.
\]
Note that $g_{2^{-j}v_j} = 2^{-pj}g_{v_j}$. Thus we finally arrive at
\[ 2^{pj}|F_j|^{p/q} \leq C \int_{\Omega} g_{v_j}(x)dx, \]
which is the desired estimate (4.1).

The fractional $(q,p)$-Sobolev-Poincaré inequality now follows from the weak type estimates via a standard argument. Write $B_y = B(y,\tau d(y,\partial\Omega))$ and $A_k = F_{k-1}\setminus F_k$.

\[ \int_{\Omega} |v(x)|^q dx \leq \sum_{k \in \mathbb{Z}} 2^{(k+1)q}|A_k| \leq C \sum_{k \in \mathbb{Z}} \left( \int_{\Omega} g_{v_k}(x)dx \right)^{q/p} \]
\[ \leq C \left( \sum_{k \in \mathbb{Z}} \int_{\Omega} g_{v_k}(x)dx \right)^{q/p} \]
\[ \leq C \left( \sum_{k \in \mathbb{Z}} (I_1^k + I_2^k) \right)^{q/p}, \]
where
\[ I_1^k = \sum_{i \leq k+1} \sum_{j \geq k+1} \int_{A_i} \int_{A_j \cap B_y} \frac{|v_k(y) - v_k(z)|^p}{|y - z|^{n+\rho}} dzdy \]
and
\[ I_2^k = \sum_{i \geq k+1} \sum_{j \geq k+1} \int_{A_i} \int_{A_j \cap B_y} \frac{|v_k(y) - v_k(z)|^p}{|y - z|^{n+\rho}} dzdy. \]
For $y \in A_i$ and $z \in A_j$ with $j - 1 > i$, $|v(y) - v(z)| \geq |v(z)| - |v(y)| \geq 2^{j-2}$. Hence,
\[ |v_k(y) - v_k(z)| \leq 2^{k+1} \leq 4 \cdot 2^{k+1-j}|v(y) - v(z)|. \]
Since the estimate
\[ |v_k(y) - v_k(z)| \leq |v(y) - v(z)| \]
holds for every $k \in \mathbb{Z}$, (4.2) is valid whenever $i \leq k \leq j$ and $(y,z) \in A_i \times A_j$. It follows from (4.2) that
\[ \sum_{k \in \mathbb{Z}} I_1^k \leq 4^p \sum_{k \in \mathbb{Z}} \sum_{i \leq k+1} \sum_{j \geq k+1} 2^{p(k+1-j)} \int_{A_i} \int_{A_j \cap B_y} \frac{|v(y) - v(z)|^p}{|y - z|^{n+\rho}} dzdy. \]
Since $\sum_{k \geq i+1} 2^{p(k+1-j)} \leq (1 - 2^{-p})^{-1}$, changing the order of the summation yields that the right hand side in the above inequality is bounded by
\[ \frac{4^p}{1 - 2^{-p}} \int_{\Omega} g_v(y)dy. \]
The estimate of $I_2^k$ is similar. Thus, we have proved that
\[ \int_{\Omega} |v(x)|^q dx \leq C \left( \int_{\Omega} g_v(y)dy \right)^{q/p}. \]
The desired fractional $(q,p)$-Sobolev-Poincaré inequality (1.4) follows from the above inequality by noticing that $|u| = v_+ + v_-$ and that $|v_+(y) - v_+(z)| \leq |u(y) - u(z)|$ for all $y,z \in \Omega$. 
The implication from condition \(ii\) to condition \(i\) is easier. To see it, fix a measurable set \(A \subset \Omega\) such that \(A \cap B_0 = \emptyset\) and a function \(u \in C(\Omega)\) such that \(u|_A \geq 1\) and \(u|_{B_0} = 0\). If \(u_\Omega \leq \frac{1}{2}\), then by (1.4) we have

\[
2^{-q}|A| \leq \int_A |u(x) - u_\Omega|^q dx \leq \int_\Omega |u(x) - u_\Omega|^q dx 
\leq C \left( \int_\Omega g_u(y) dy \right)^{q/p}.
\]

If \(u_\Omega \geq \frac{1}{2}\), then by (1.4) we have

\[
2^{-q}|A| \leq 2^{-q} \frac{[\Omega]}{|B_0|} |B_0| \leq \frac{[\Omega]}{|B_0|} \int_{B_0} |u(x) - u_\Omega|^q dx 
\leq \frac{[\Omega]}{|B_0|} C \left( \int_\Omega g_u(y) dy \right)^{q/p}.
\]

Combining the above two estimates, we conclude that

\[
|A|^{p/q} \leq C \int_\Omega g_u(x) dx,
\]

where \(C = C(\Omega, B_0, p, q)\). Taking the infimum over all such \(u\) gives us (1.6).

\[\square\]

**Proof of Theorem 1.2.** Let \(B_0 = B(x_0, \frac{d(x_0, \partial_\Omega)}{\tau})\). Assume that \(p < n/\delta\), \(1 < s < \frac{n}{n - p\delta}\) and \(1 \leq p \leq q < \frac{np}{s(n - p\delta) + (s - 1)(p - 1)}\). Choose \(\Delta > 0\) such that

\[
2\Delta = \frac{np}{q} - s(n - p\delta) - (s - 1)(p - 1).
\]

It suffices to show, by Theorem 1.1, that there exists a constant \(C = C(\Omega, p, q, B_0)\) such that for every measurable set \(A \subset \Omega\) with \(A \cap B_0 = \emptyset\), we have

\[
|A|^{p/q} \leq C \inf \int_\Omega g_u(x) dx
\]

whenever \(u \in C(\Omega)\) satisfies \(u|_A \geq 1\) and \(u|_{B_0} = 0\).

For any \(x \in A\), we obtain from Lemma 3.1 a finite chain of balls \(B_i, i = 0, 1, \cdots, k\), satisfying conditions 1-6 with \(M > 2/\tau\). For all \(i = 0, 1, \cdots, k\), we have

\[
(4.3) \quad B_i \subset B(y, \tau d(y, \partial_\Omega)), \quad \text{if} \ y \in B_i.
\]

To see this, fix \(y \in B_i\) and let \(z\) be any other point in \(B_i\), then by condition 3 in Lemma 3.1

\[
|z - y| \leq |y - x_i| + |x_i - z| \leq 2r_i \leq 2 \frac{d(B_i, \partial_\Omega)}{M} 
\leq \frac{2}{M} d(y, \partial_\Omega) < \tau d(y, \partial_\Omega).
\]

In order to estimate \(|A|\), we divide \(A\) into the “bad” and “good” parts. Set

\[
\mathcal{G} = \left\{ x \in A | u_{B_0} \geq \frac{1}{2} \right\} \quad \text{and} \quad \mathcal{B} = A \setminus \mathcal{G}.
\]

We have \(|A| \leq |\mathcal{G}| + |\mathcal{B}|\) and we first estimate \(|\mathcal{G}|\).
By condition 1 in Lemma 3.1 we have
\[
\frac{1}{2} \leq |u_{B_k} - u_{B_0}| \leq \sum_{i=0}^{k-1} |u_{B_i} - u_{B_{i+1}}| \\
\leq \sum_{i=0}^{k-1} \left( |u_{B_i} - u_{B_i \cap B_{i+1}}| + |u_{B_{i+1}} - u_{B_i \cap B_{i+1}}| \right) \\
\lesssim \sum_{i=0}^{k} \frac{1}{|B_i|} \int_{B_i} |u(y) - u_{B_i}| \, dy.
\]

For a ball \(B_i\),
\[
\frac{1}{|B_i|} \int_{B_i} |u(y) - u_{B_i}| \, dy \leq \frac{1}{|B_i|} \int_{B_i} \left( \frac{1}{|B_i|} \int_{B_i} |u(y) - u(z)|^p \, dz \right)^{1/p} \, dy \\
= \frac{1}{|B_i|^{1+1/p}} \int_{B_i} \left( \int_{B_i} |u(y) - u(z)|^p \, dz \right)^{1/p} \, dy \\
\lesssim |B_i|^{\delta/n-1} \int_{B_i} \left( \int_{B_i} \frac{|u(y) - u(z)|^p}{|y-z|^{n+p\delta}} \, dz \right)^{1/p} \, dy.
\]

Set
\[
g(y) := \left( \int_{\Omega \setminus B(y, \tau d(y, \partial \Omega))} \frac{|u(y) - u(z)|^p}{|y-z|^{n+p\delta}} \, dz \right)^{1/p},
\]

By (4.3) and condition 2 in Lemma 3.1,
\[
\sum_{i=0}^{k} \frac{1}{|B_i|} \int_{B_i} |u(y) - u_{B_i}| \, dy \\
\lesssim \sum_{i=0}^{k} |B_i|^{\delta/n-1} \int_{B_i} \left( \int_{B_i} \frac{|u(y) - u(z)|^p}{|y-z|^{n+p\delta}} \, dz \right)^{1/p} \, dy \\
\leq \sum_{i=0}^{k} |B_i|^{\delta/n-1} \int_{B_i} \left( \int_{B(y, \tau d(y, \partial \Omega))} \frac{|u(y) - u(z)|^p}{|y-z|^{n+p\delta}} \, dz \right)^{1/p} \, dy \\
\lesssim \sum_{i=0}^{k} r_i^{\delta-n/p} \left( \int_{B_i} g(y)^p \, dy \right)^{1/p}.
\]

Thus we conclude that
\[
1 \lesssim \sum_{i=0}^{k} r_i^{\delta-n/p} \left( \int_{B_i} g(y)^p \, dy \right)^{1/p}.
\]

Hölder’s inequality implies
\[
1 \lesssim \left( \sum_{i=0}^{k} r_i^{\kappa p/(p-1)} \right)^{(p-1)/p} \left( \sum_{i=0}^{k} r_i^{p(-\kappa+\delta-n/p)} \int_{B_i} g(y)^p \, dy \right)^{1/p},
\]
where \(\kappa = \frac{(s-1)(p-1) + \Delta}{sp}\). Using condition 6 from Lemma 3.1 one can easily conclude
\[
\sum_{i=0}^{k} r_i^{\kappa p/(p-1)} \leq \sum_{i=0}^{\infty} (2^{-i})^{\kappa p/(p-1)} 2^{i(s-1)/s} < C.
\]
Therefore,

\[ (4.4) \quad \sum_{i=0}^{k} r_i^{(\kappa+\delta-n/p)} \int_{B_i} g(y)^p \, dy \geq C, \]

where the constant \(C\) depends only on \(p, n, \Delta\) and the constant from \(s\)-John condition.

By condition 2 from Lemma 3.1, \(Cr_i \geq |x-y|^s\), for \(y \in B_i\), and since \(p(-\kappa + \delta - n/p) < 0\) according to our choice \(p \leq n/\delta\), we obtain

\[ r_i^{-\kappa p-n+\delta} \lesssim |x-y|^{s(-\kappa p-n+p\delta)} \]

for \(y \in B_i\). For \(y \in B_i \cap (2^{j+1}B_k \setminus 2^j B_k)\), we have \(|x-y| \approx 2^j r_k\) and hence for such \(y\),

\[ (4.5) \quad r_i^{-\kappa p-n+p\delta} \lesssim (2^j r_k)^{s(-\kappa p-n+p\delta)}. \]

Combining (4.4) with (4.5) leads to

\[ \frac{1}{2^j r_k} \lesssim \sum_{i=0}^{k} r_i^{(\kappa+\delta-n/p)} \int_{B_i} g(y)^p \, dy \lesssim (r_k)^{s(-\kappa p-n+p\delta)} \int_{B_i} g(y)^p \, dy \]

On the other hand,

\[ \frac{1}{2^j r_k} \lesssim \sum_{i=0}^{k} r_i^{(\kappa+\delta-n/p)} \int_{B_i} g(y)^p \, dy \lesssim (r_k)^{s(-\kappa p-n+p\delta)} \int_{B_i} g(y)^p \, dy. \]

Comparing the above two estimates, we conclude that there exists an \(l\) (depending on \(\Delta\)) such that

\[ (2^l r_k)^{s(-\kappa p-n+p\delta)} \int_{2^l B_k \cap \Omega} g(y)^p \, dy. \]

It follows that,

\[ \int_{\Omega \cap 2^l B_k} g(y)^p \, dy \gtrsim (2^l r_k)^{s(n+p\delta)+\Delta} = (2^l r_k)^{s(n-p\delta)+(s-1)(p-1)+2\Delta}. \]

In other words, there exists an \(R_x = d(x, \partial \Omega)/2\) with

\[ \left( \int_{\Omega \cap B(x, R_x)} g(y)^p \, dy \right)^{\frac{1}{(s(n-p\delta)+(s-1)(p-1)+2\Delta)}} \gtrsim (R_x^n)^{p/q}. \]

Note that according to our choice of \(\Delta\), the above estimate reduces to the following form:

\[ \int_{\Omega \cap B(x, R_x)} g(y)^p \, dy \gtrsim |B(x, R_x)|^{p/q}. \]
Applying the Vitali covering lemma to the covering \( \{ B(x, R_x) \}_{x \in E} \) of the set \( \mathcal{B} \), we can select pairwise disjoint balls \( B_1, \ldots, B_k, \ldots \) such that \( \mathcal{B} \subset \bigcup_{i=1}^{\infty} 5B_i \). Let \( r_i \) denote the radius of the ball \( B_i \). Then

\[
|\mathcal{G}| \leq \sum_{i=1}^{\infty} |5B_i| = 5^n \sum_{i=1}^{\infty} |B_i| \lesssim \sum_{i=1}^{\infty} \left( \int_{\Omega \cap B_i} g_u(y)\,dy \right)^{\frac{q}{p}}
\]

\[
\lesssim \left( \sum_{i=1}^{\infty} \int_{\Omega \cap B_i} g_u(y)\,dy \right)^{\frac{q}{p}} \lesssim \left( \int_{\Omega} g_u(y)\,dy \right)^{\frac{q}{p}}.
\]

We next estimate \( |\mathcal{G}| \). Note that \( \mathcal{B} \subset \bigcup_{x \in \mathcal{B}} B_x \). We may use the Besicovitch covering theorem to select a subcovering \( \{ B_{x_i} \}_{i \in \mathbb{N}} \). Since \( u \geq 1 \) on \( A \), and \( u_{B_{x_i}} \leq \frac{1}{2} \), we obtain that

\[
|u(y) - u_{B_{x_i}}| \geq 2^{-q}
\]

for \( y \in A \cap B_{x_i} \). By the fractional \((q, p)\)-Sobolev-Poincaré inequality for balls, we get

\[
|A \cap B_{x_i}| \leq C \int_{A \cap B_{x_i}} |u(y) - u_{B_{x_i}}|^q\,dy
\]

\[
\leq C \left( \int_{B_{x_i}} g_u(y)\,dy \right)^{q/p}.
\]

Summing over all balls \( B_{x_i} \), we obtain that

\[
|\mathcal{B}|^{p/q} \leq C \int_{\Omega} g_u(y)\,dy.
\]

The proof of Theorem 1.2 is now complete.

\[ \square \]

Remark 4.1. In Theorem 1.2, \( q \) is assumed to be strictly less than \( \frac{np}{s(n-p0) - (s-1)(p-1)} \). However, one can easily adapt the proof of Theorem 1.2 to show that when \( s = 1 \) or \( p = 1 \), \( q \) can reach the critical value. Indeed, we only need to use a variant of Lemma 3.1. Namely, for each \( x \in \Omega \), we may join \( x \) to \( x_0 \) via an infinite chain of balls \( \{ B_i \}_{i \in \mathbb{N}} \) with all the properties listed in Lemma 3.1 except condition 5 replaced with

\[
|x - x_i| \leq cr_i^{1/s} \to 0
\]

as \( i \to \infty \). Then following the proof of Theorem 1.2 we easily deduce the following Riesz potential type estimate:

\[
|u(x) - u_{B_0}| \lesssim \sum_{i=1}^{\infty} r_i^{\delta - n} \int_{B_i} g(y)\,dy \lesssim \int_{\Omega} \frac{g(y)}{|x - y|^{s(n-\delta)}}\,dy.
\]

Note that

\[
\int_{\Omega} \frac{g(y)}{|x - y|^{s(n-\delta)}}\,dy = I_\delta(\chi_\Omega g)(x).
\]

Thus we conclude that

\[
|u(x) - u_{B_0}| \lesssim I_\delta(\chi_\Omega g)(x).
\]

For \( s = 1 \) and \( p > 1 \), the claim follows from the strong type estimate in Theorem 3.2. For \( p = 1 \), the claim follows from the weak type estimate (3.2).
Proof of Example 1.3. We will use the mushroom-like domain as used in [7]. The mushroom-like domain \( \Omega \subset \mathbb{R}^n \) consists of a cube \( Q \) and an attached infinite sequence of mushrooms \( F_1, F_2, \ldots \) growing on the “top” of the cube. By a mushroom \( F \) of size \( r \), we mean a cap \( C \), which is a ball of radius \( r \), and an attached cylindrical stem \( \mathcal{P} \) of height \( r \) and radius \( r^s \). The mushrooms are disjoint, and the corresponding cylinders are perpendicular to the side of the cube that we have selected as the top of the cube. We can make the mushrooms pairwise disjoint if the number \( r_i \) associated with \( F_i \) converges to 0 sufficiently fast as \( i \to \infty \).

Let \( u_i \) be a piecewise linear function on \( \Omega \) such that \( u_i = 0 \) outside \( F_i \), \( u_i = 1 \) on the cap \( C_i \), and \( u_i \) is linear on the associated cylinder \( \mathcal{P}_i \). Assume that \( 1 \leq s < \frac{n}{n-p} \), and that one can prove the fractional \((q, p)\)-Sobolev-Poincaré inequality with \( q > \frac{s(n-p) + (s-1)(p-1)}{p} \).

Note that
\[
\left( \int_\Omega |u(x) - u_\Omega|^q \, dx \right)^{1/q} \gtrsim r_i^{n/q}.
\]
On the other hand,
\[
\left( \int_\Omega \int_{\Omega \cap B(x, d(x, \partial \Omega))} \frac{|u(x) - u(y)|^p}{|x - y|^{n+p}} \, dx \right)^{1/p} \lesssim \left( r_i^{-p} \int_{\mathcal{P}_i} d(x, \partial \Omega)^{p(1-\delta)} \, dx \right)^{1/p} \lesssim \left( r_i^{s(n-p) + (s-1)(p-1)} \right)^{1/p}.
\]
Thus we obtain that for all \( i \in \mathbb{N} \)
\[
r_i^{n/q} \lesssim \left( r_i^{s(n-p) + (s-1)(p-1)} \right)^{1/p},
\]
which is impossible if \( q > \frac{s(n-p) + (s-1)(p-1)}{p} \).

\[\square\]

5. Fractional \((q, p)\)-Sobolev-Poincaré inequalities in domains with quasi-hyperbolic boundary condition

Recall that a domain \( \Omega \subset \mathbb{R}^n \), \( n \geq 2 \), is said to satisfy a \( \beta \)-quasi-hyperbolic boundary condition, \( \beta \in (0, 1] \), if there exist a point \( x_0 \in \Omega \) and a constant \( C_0 \) such that
\[
k_\Omega(x, x_0) \leq \frac{1}{\beta} \log \frac{d(x_0, \partial \Omega)}{d(x, \partial \Omega)} + C_0
\]
holds for all \( x \in \Omega \).

Proof of Theorem 1.4. Fix \( Q_0 \subset \Omega \) the central Whitney cube containing \( x_0 \). For each measurable set \( A \subset \Omega \) with \( A \cap Q_0 = \emptyset \), let \( u \in C(\Omega) \) satisfy \( u_{|A} \geq 1 \) and \( u_{|Q_0} = 0 \). As in the proof of Theorem 1.2, we divide \( A \) into “good” and “bad” parts. Set
\[
\mathcal{G} = \left\{ x \in A | u_{Q} \geq \frac{1}{2} \text{ for some Whitney cube } Q \ni x \right\} \text{ and } \mathcal{B} = A \backslash \mathcal{G}.
\]
We have $|A| \leq |\mathcal{G}| + |\mathcal{R}|$ and we first estimate $|\mathcal{R}|$.

For points $x \in \mathcal{R}$, the standard fractional $(p', p)$-Sobolev-Poincaré inequality on cubes provides a trivial estimate

$$|A \cap Q|^{1/p'} \leq C \left( \int_Q |u - u_Q|^{p'} \, dy \right)^{1/p} \leq C \left( \int_Q g_u(y) \, dy \right)^{1/p}$$

on Whitney cube $Q$ containing $x$. Since $q < p'$ this yields

$$\int_Q g_u(y) \, dy \geq \frac{1}{C} |A \cap Q|^{p/q}$$

and by summing over all such Whitney cubes we deduce that

$$\int_\Omega g_u(y) \, dy \geq \frac{1}{C} |\mathcal{R}|^{p/q}.$$

We next estimate $|\mathcal{G}|$ and our aim is to show that

$$\int_\Omega g_u(y) \, dy \geq \frac{1}{C} |\mathcal{G}|^{p/q},$$

and then the conclusion follows from Theorem 1.1.

For each $x \in \mathcal{G}$, let $Q(x)$ be the Whitney cube containing $x$ for which $u_{Q(x)} \geq \frac{1}{2}$. Then the chaining argument used in the proof of Theorem 1.2 gives us the estimate

$$1 \lesssim \sum_{Q \in P(Q(x))} (\text{diam } Q)^{\delta-n/p} \left( \int_Q g_u(y) \, dy \right)^{1/p};$$

recall that $P(Q(x))$ consists of the collection of all the Whitney cubes which intersect the quasihyperbolic geodesic joining $x_0$ to the center of $Q(x)$.

Integrating (5.4) with respect to the Lebesgue measure and interchanging the order of summation and integration yields

$$|\mathcal{G}| \lesssim \int_\mathcal{G} \sum_{Q \in P(Q(x))} (\text{diam } Q)^{\delta-n/p} \left( \int_Q g_u(y) \, dy \right)^{1/p} \, dx$$

$$\leq \sum_{Q \in \mathcal{W}} |S(Q) \cap \mathcal{G}| (\text{diam } Q)^{\delta-n/p} \left( \int_Q g_u(y) \, dy \right)^{1/p}.$$

Applying Hölder’s inequality leads to

$$|\mathcal{G}| \lesssim \left( \sum_{Q \in \mathcal{W}} |S(Q) \cap \mathcal{G}| \frac{p}{p'} |Q|^{-\frac{n-\delta}{p'}} \right)^{\frac{p}{p-1}} \left( \sum_{Q \in \mathcal{W}} \int_Q g_u(y) \, dy \right)^{\frac{1}{p}}$$

$$\leq \left( \sum_{Q \in \mathcal{W}} |S(Q) \cap \mathcal{G}|^{\frac{p}{p'}} |Q|^{-\frac{n-\delta}{p'}} \right)^{\frac{p}{p-1}} \left( \int_\Omega g_u(y) \, dy \right)^{\frac{1}{p}}.$$

Applying Lemma 5.1 below, we find that

$$|\mathcal{G}| \lesssim |\mathcal{G}|^{(q-1)/q} \left( \int_\Omega g_u(y) \, dy \right)^{\frac{1}{p}},$$

which proves (5.3).
Lemma 5.1. Fix $p$ and $q$ as in Theorem 1.4. Then there exists a constant $C = C(n, p, q, \beta)$ such that

$$\sum_{Q \in \mathcal{W}} |S(Q) \cap E|^{\frac{q}{\beta q}} |Q|^{\frac{p q}{p q - p \delta}} \leq C |E|^{\frac{p q}{p q - p \delta}}$$

whenever $E \subset \Omega$.

Proof. For simplicity, we write $p^* = \frac{n p}{n - p \delta}$, $\kappa = \frac{p}{p - 1}$ and $\lambda = \frac{q}{q - 1}$. Then $\frac{n - p \delta}{n(p - 1)} = \frac{\kappa}{p^*}$. Thus

$$\sum_{Q \in \mathcal{W}} |S(Q) \cap E|^{\frac{q}{\beta q}} |Q|^{\frac{p q}{p q - p \delta}} \leq |E|^{\frac{q}{\beta q}} \sum_{Q \in \mathcal{W}} |Q_1 \cap E| \left( \frac{|S(Q)|^{\frac{1}{\beta}}}{|Q|^{\frac{\kappa}{p^*}}} \right)^\kappa$$

$$\leq |E|^{\frac{q}{\beta q}} \sum_{Q_1 \in \mathcal{W}} |Q_1 \cap E| \sum_{Q \in \mathcal{P}(Q_1)} |Q| \left( \frac{|S(Q)|^{\frac{1}{\beta}}}{|Q|^{\frac{\kappa}{p^*}}} \right)^\kappa$$

$$\leq |E|^{\frac{q}{\beta q}} \sum_{Q_1 \in \mathcal{W}} |Q_1 \cap E| = |E|^{\frac{q}{\beta q}},$$

where we have used (3.3) and (3.3) with $\varepsilon = (\frac{2\beta}{(1 + \beta)q} - \frac{1}{p^*})\kappa > 0$.

Proof of Example 1.5. The construction here is similar to that used in the proof of Example 1.3 and thus we only point out the difference. The mushroom-like domain $\Omega \subset \mathbb{R}^n$ consists of a cube $Q$ and an attached infinite sequences of mushrooms $F_1, F_2, \cdots$ growing on the “top” of the cube as in Example 1.3. Now, by a mushroom $F$ of size $r$, we mean a cap $C$, which is a ball of radius $r$, and an attached cylindrical stem $P$ of height $r^\tau$ and radius $r^\sigma$. The mushrooms are disjoint, and the corresponding cylinders are perpendicular to the side of the cube that we have selected as the top of the cube. We can make the mushrooms pairwise disjoint if the number $r_i$ associated with $F_i$ converges to 0 sufficiently fast as $i \to \infty$.

It is easy to show that $\Omega$ satisfies the $\beta$-quasihyperbolic boundary condition (5.1) if $\sigma = \frac{1 + \beta}{2\beta} \leq \tau$; see for instance [13] Example 5.5. We next show that $\Omega$ is not a fractional $(q, p)$-Sobolev-Poincaré domain if

$$q > \frac{np}{\sigma(n - p \delta) + (p - 1)(\sigma - \tau)}.$$  

When $\tau = \sigma = \frac{1 + \beta}{2\beta}$, (5.6) implies that $\Omega$ is a $\beta$-quasihyperbolic boundary condition boundary which does not support a fractional $(q, p)$-Sobolev-Poincaré inequality. This verifies Example 1.5.

Let $u_i$ be a piecewise linear function on $\Omega$ such that $u_i = 0$ outside $F_i$, $u_i = 1$ on the cap $C_i$, and $u_i$ is linear on the associated cylinder $P_i$. Assume that the fractional $(q, p)$-Sobolev-Poincaré inequality holds on $\Omega$.

Note that

$$\left( \int_{\Omega} |u(x) - u_\Omega|^q dx \right)^{1/q} \gtrsim r_i^{n/q}.$$
On the other hand,

\[
\left( \int_\Omega \int_{B(x,r(\partial B))} \frac{|u(x) - u(y)|^p}{|x - y|^{n + p\delta}} \, dx \right)^{1/p} = \left( \int_{\mathbb{R}^n} \int_{B(x,r(\partial B))} \frac{|u(x) - u(y)|^p}{|x - y|^{n + p\delta}} \, dx \right)^{1/p} \leq \left( r_i^{-p} \int_{\mathbb{R}^n} d(x, \partial B)^{p(1 - \delta)} \, dx \right)^{1/p} \leq \left( t_i^{\sigma(n - p\delta) + (p - 1)(\sigma - \tau)} \right)^{1/p}.
\]

Thus we obtain that for all \( i \in \mathbb{N} \)

\[
y_i^{\frac{n}{q}} \leq t_i^{\frac{\sigma(n - p\delta) + (p - 1)(\sigma - \tau)}{p}},
\]

which is impossible if \( q > \frac{np}{\sigma(n - p\delta) + (\sigma - \tau)(p - 1)} \).

\[\square\]

6. Necessary Conditions for the Fractional \((q, p)\)-Sobolev-Poincaré Domains

**Proof of Theorem 1.6.** Fix \( x \in \Omega \). Pick a curve \( \gamma : [0, 1] \to \Omega \) with \( \gamma(0) = x \) and \( \gamma(1) = x_0 \) as in the definition of separation property.

Let \( 0 < t < 1 \) and \( \delta(t) = d(\gamma(t), C\delta(t)) \), there is nothing to prove. Otherwise, the separation property implies that \( \partial B = \partial B(\gamma(t), C\delta(t)) \) separates \( \gamma([0, t]) \setminus B \) from \( x_0 \). If the component of \( \Omega \setminus \partial B \) containing \( x_0 \) does not contain a ball centred at \( x_0 \) of radius \( \delta(1)/2 \), then \( B \) must have radius at least \( \delta(1)/4 \) since it intersects both \( B(x_0, \delta(1)/2) \) and \( \partial \Omega \). In this case, \( B' = 4B \) contains \( B(x_0, \delta(1)/4) \) and we may assume that \( B' \) does not contain \( \gamma([0, t]) \) (since otherwise we are done). Thus either \( \Omega \setminus \partial B \) or \( B' \) contains a ball centred at \( x_0 \) of radius comparable to \( \delta(1) \). In either cases, we conclude from Proposition 3.3 that

\[
diam \gamma([0, t]) \leq C \varphi(d(\gamma(t), \partial \Omega)),
\]

where \( \varphi(t) = t^{(\frac{n - p\delta}{p})(\frac{1}{p} - \frac{1}{4})} \). \(\square\)

A bounded domain \( \Omega \subset \mathbb{R}^n \) with a distinguished point \( x_0 \) satisfying \( \varphi(t) = t^{1/s} \) is termed s-diam John in \( \mathbb{R}^n \). It was proved in \( \mathbb{R}^n \) that, for \( s > 1 \), s-diam John domains are not necessarily s-John.

In \( \mathbb{R}^n \), \( n \geq 4 \), it was stated that if a bounded domain \( \Omega \subset \mathbb{R}^n \) satisfies a separation property and supports a \((q, p)\)-Sobolev-Poincaré inequality \((1.3)\) with \( q > p \), then \( \Omega \) is s-John with \( s = \frac{p}{(n - p)(q - p)} \). One could immediately check that the proof given there was only sufficient to deduce that \( \Omega \) is s-diam John with \( s = \frac{p}{(n - p)(q - p)} \). In fact, combining \( \mathbb{R}^n \) Example 5.1 and \( \mathbb{R}^n \) Section 4, one can produce an s-diam John domain \( \Omega \subset \mathbb{R}^n \) with \( s = \frac{p}{(n - p)(q - p)} \) such that \( \Omega \) supports a \((q, p)\)-Sobolev-Poincaré inequality. Moreover, \( \Omega \) is not s'-diam John whenever \( s' < s \) and \( \Omega \) is not s-John.

We next briefly discuss how to construct such an example in the plane (it works in higher dimensions as well). Set

\[
C(r; \alpha, \beta) = C(r) = \{(x_1, x) : 0 < x_1 < r^\alpha, |x'| < r^\beta \},
\]
where $0 < \alpha < \beta \leq 1$ will be specified later. The idea is very simple, we first use the mushroom-like domain $\Omega' \subset \mathbb{R}^2$ constructed as in [2] (with different choices of parameters) and then modify $\Omega'$ to be a spiral domain $\Omega$ as in [3, Example 5.1].

The mushroom-like domain $\Omega' \subset \mathbb{R}^2$ consists of a cube $Q$ and an attached infinite sequences of mushrooms $F_1, F_2, \ldots$ growing on the “top” of the cube as in Example 1.3. Now, by a mushroom $F$ of size $r$, we mean a cap $C$, which is a ball of radius $r$, and an attached cylindrical stem $C(r)$. The mushrooms are disjoint, and the corresponding cylinders are perpendicular to the side of the cube that we have selected as the top of the cube. We can make the mushrooms pairwise disjoint if the number $r_i$ associated with $F_i$ converges to 0 sufficiently fast as $i \to \infty$.

Note first that if $\beta = \alpha \frac{p+(p-1)q}{(n-1)(q-p)}$ with $n = 2$, then $C(r)$ satisfies the $(q, p)$-Sobolev-Poincaré inequality uniformly in $r$; see [2]. Let $\mu = s\beta = \frac{p^2}{(2-p)(q-p)}\beta$ and $p^* = \frac{np}{n-p}$. One can show that $\Omega'$ is a $(q, p)$-Sobolev-Poincaré domain if

$$\alpha + \beta(n - 1) - \frac{nq}{p^*} > 0$$

(6.1) holds with $n = 2$; see [2]. Note also that $\Omega$ is $\frac{1}{s}$-John.

We next bend each mushroom $F_i$ to make it spiralling so that the resulting domain $\Omega$ is an $s$-diam John domain. According to our choice, $s = \frac{4}{p}$. One can check that if $\beta = \alpha \frac{p+(p-1)q}{q-p}$, then (6.1) reduces to

$$\frac{1}{\beta} < \frac{p^2}{(2-p)[p+(p-1)q]}.$$ 

(6.2)

Since $p < q < p^*$, $\frac{p^2}{(2-p)[p+(p-1)q]} > 1$. For any $\beta$ satisfies (6.2) and $\beta = \alpha \frac{p+(p-1)q}{q-p}$. It is easy to check that $\frac{1}{\alpha} > s = \frac{4}{p}$. It is clear that $\Omega'$ and $\Omega$ are bi-Lipschitz equivalent and so the $(q, p)$-Sobolev-Poincaré inequality holds in $\Omega$ as well. Moreover, $\Omega$ satisfies all the required properties.

One could also modify the above example to the fractional $(q, p)$-Sobolev-Poincaré case, but the computations will be too complicated and so we omit it in the present paper.

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