Higher Dimensional Techniques for the Regularity of Maximal Functions

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Introduction: Background

For $f : \mathbb{R}^n \to \mathbb{R}$ the centered Hardy-Littlewood maximal function is defined by

$$\mathrm{M}^{\mathrm{c}} f(x) = \sup_{r>0} f_{B(x,r)} \quad \text{with} \qquad f_{B(x,r)} = \frac{1}{\mathcal{L}(B(x,r))} \int_{B(x,r)} |f|.$$

Theorem (Hardy-Littlewood maximal function theorem)

$$\|\mathrm{M}^{\mathrm{c}} f\|_{L^p(\mathbb{R}^n)} \lesssim_{n,p} \|f\|_{L^p(\mathbb{R}^n)}$$

if and only if $p > 1$.

$$\|\mathrm{M}^{\mathrm{c}} f\|_{L^{1,\infty}(\mathbb{R}^n)} \lesssim_{n} \|f\|_{L^1(\mathbb{R}^n)}$$

Introduction: Background

Theorem (Juha Kinnunen (1997))

For $p > 1$ we have

$$\|\nabla \mathrm{M}^{\mathrm{c}} f\|_{L^p(\mathbb{R}^n)} \lesssim_{n,p} \|\nabla f\|_{L^p(\mathbb{R}^n)}$$

Proof: For $e \in \mathbb{R}^n$ by the sublinearity of M^{c}

$$\begin{aligned}
\partial_e \mathrm{M}^{\mathrm{c}} f(x) &\sim \frac{\mathrm{M}^{\mathrm{c}} f(x+he) - \mathrm{M}^{\mathrm{c}} f(x)}{h} \\
&\leq \frac{\mathrm{M}^{\mathrm{c}}(f(\cdot + he) - f)(x)}{h} \\
&= \mathrm{M}^{\mathrm{c}}\Big(\frac{f(\cdot + he) - f}{h}\Big)(x) \sim \mathrm{M}^{\mathrm{c}}(\partial_e f)(x)
\end{aligned}$$

By the Hardy-Littlewood maximal function theorem for $p > 1$

$$\|\nabla \mathrm{M}^{\mathrm{c}} f\|_{L^p(\mathbb{R}^n)} \leq \|\mathrm{M}^{\mathrm{c}}(|\nabla f|)\|_{L^p(\mathbb{R}^n)} \lesssim_{n,p} \|\nabla f\|_{L^p(\mathbb{R}^n)}$$

Introduction: Background

Question (Hajłasz and Onninen 2004)

Is it true that

$$\|\nabla \mathrm{M}^{\mathrm{c}} f\|_{L^1(\mathbb{R}^n)} \lesssim_n \|\nabla f\|_{L^1(\mathbb{R}^n)}?$$

Uncentered Hardy-Littlewood maximal function

$$\widetilde{\mathrm{M}} f(x) = \sup_{B \ni x} f_B.$$

Endpoint question by Hałjasz and Onninen is interesting for $\widetilde{\mathrm{M}}$ and other maximal operators.

Introduction: In one dimension

Theorem (Tanaka 2002, Aldaz and Pérez Lázaro 2007)

For $f : \mathbb{R} \to \mathbb{R}$ *we have*

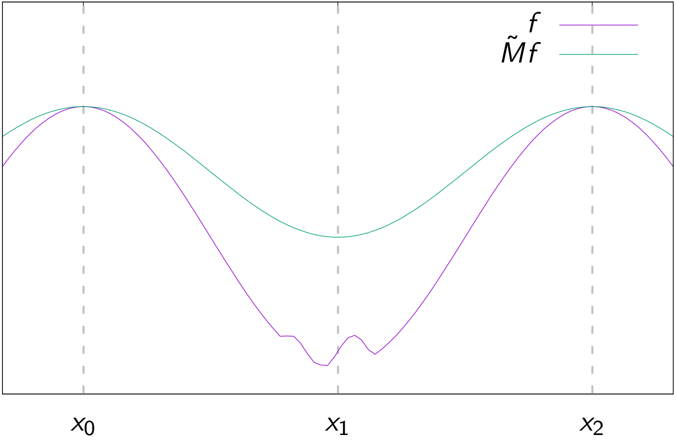
$$\|\nabla \widetilde{\mathrm{M}} f\|_1 \leq \|\nabla f\|_1$$

Proof:

- In one dimension

$$\|\nabla f\|_1 = \sup_{x_1 < x_2 < \dots} \sum_i |f(x_{i+1}) - f(x_i)| = \operatorname{var} f.$$

- For almost all $x \in \mathbb{R}^d$: $\widetilde{\mathrm{M}} f(x) \geq f(x)$
- and $\widetilde{\mathrm{M}} f(x) = f(x)$ at a strict local maximum of $\mathrm{M} f$.



$$
\begin{aligned}
\operatorname{var}_{[x_0,x_2]} \widetilde{\mathrm{M}} f &= |\widetilde{\mathrm{M}} f(x_1) - \widetilde{\mathrm{M}} f(x_0)| + |\widetilde{\mathrm{M}} f(x_2) - \widetilde{\mathrm{M}} f(x_1)| \\
&\leq |f(x_1) - f(x_0)| + |f(x_2) - f(x_1)| \\
&\leq \operatorname{var}_{[x_0,x_2]} f
\end{aligned}
$$

For $0 < \alpha < n$ the centered fractional Hardy-Littlewood maximal function is

$$\mathrm{M}_\alpha^{\mathrm{c}} f(x) = \sup_{r>0} r^\alpha f_{B(x,r)}.$$

Corresponding Hardy-Littlewood theorem

$$\|\mathrm{M}_\alpha f\|_{L^{p_\alpha}(\mathbb{R}^n)} \lesssim_{n,\alpha,p} \|f\|_{L^p(\mathbb{R}^n)}$$

with $p_\alpha = \frac{pn}{n-\alpha p} > p$ if and only if $p > 1$. Corresponding regularity bound

$$\|\nabla \mathrm{M}_\alpha f\|_{L^{p_\alpha}(\mathbb{R}^n)} \lesssim_{n,\alpha,p} \|\nabla f\|_{L^p(\mathbb{R}^n)},$$

proven for $p > 1$.

Theorem (Kinnunen and Saksman 2003)

For $\alpha \geq 1$
$$|\nabla \mathrm{M}_\alpha^{\mathrm{c}} f(x)| \lesssim_n |\mathrm{M}_{\alpha-1}^{\mathrm{c}} f(x)|.$$

Corollary (Carneiro and Madrid 2016)

For $\alpha \geq 1$ we have $1_\alpha = \frac{n}{n-\alpha} = \left(\frac{n}{n-1}\right)_{\alpha-1}$ and $\frac{n}{n-1} > 1$ and therefore

$$\|\nabla \mathrm{M}_\alpha^{\mathrm{c}} f\|_{L^{1_\alpha}(\mathbb{R}^n)} \lesssim_n \|\mathrm{M}_{\alpha-1}^{\mathrm{c}} f\|_{L^{1_\alpha}(\mathbb{R}^n)} \lesssim_n \|f\|_{L^{\frac{n}{n-1}}(\mathbb{R}^n)}$$
$$\lesssim_n \|\nabla f\|_{L^1(\mathbb{R}^n)}.$$

- What about $0 < \alpha < 1$?
- Same result for $\widetilde{\mathrm{M}}_\alpha$.

Introduction: Past progress

$n = 1$	[Tanaka 2002, Aldaz +Pérez Lázaro 2007]
block decreasing f	[Aldaz+Pérez Lázaro 2009]
centered M, $n = 1$	[Kurka 2015]
radial f	[Luiro 2018]
fractional:	
$n = 1$	[Beltran + Madrid 2016]
$1 \leq \alpha$	[Kinnunen + Saksman 2003, Carneiro + Madrid 2016]
radial f	[Luiro + Madrid 2017]
lacunary	[Beltran + Ramos + Saari 2018]
$n = 1$, radial for centered f	[Beltran + Madrid 2019]

- bounds on other maximal operators, such as local, . . . ,
- local regularity and smoothing, i.e. does $f \mapsto \nabla \mathrm{M} f$ map $\mathrm{BV}(\mathbb{R}^n) \to L^1(\mathbb{R}^n)$ or only into Radon measures?
- operator continuity of $f \mapsto \nabla \mathrm{M} f$ on $W^{1,1}(\mathbb{R}^n) \to L^1(\mathbb{R}^n)$, stronger than boundedness.

Continuity

Stronger property than boundedness:

Operator continuity of M

f close to g $\quad\Rightarrow\quad$ $\mathrm{M}f$ close to $\mathrm{M}g$?

By sublinearity

$$\mathrm{M}f(x) - \mathrm{M}g(x) \leq \mathrm{M}(f-g)(x) + \mathrm{M}g(x) - \mathrm{M}g(x)$$

and thus

$$\|\mathrm{M}f - \mathrm{M}g\|_{L^p(\mathbb{R}^n)} \leq \|\mathrm{M}(f-g)\|_{L^p(\mathbb{R}^n)} \lesssim_{n,p} \|f-g\|_{L^p(\mathbb{R}^n)}.$$

Continuity

However,

$$|\nabla \mathrm{M} f(x) - \nabla \mathrm{M} g(x)| \not\lesssim |\nabla \mathrm{M}(f - g)(x)|.$$

Nevertheless, [Luiro 2004] proved for $p > 1$ that

$$\|f_n - f\|_{W^{1,p}(\mathbb{R}^n)} \to 0 \quad \Longrightarrow \quad \|\nabla \mathrm{M} f_n - \nabla \mathrm{M} f\|_{L^p(\mathbb{R}^n)} \to 0.$$

Operator continuity is now known in almost the same cases as boundedness due to many results by [Beltran, Carneiro, González-Riquelme, Madrid, Pierce,... 2013–].

Introduction: New results

We prove the endpoint regularity bound for the maximal function for

1. uncentered maximal function of characteristic f
2. dyadic maximal operator
3. fractional maximal operator (uncentered & centered)
4. cube maximal operator

Introduction: Reformulation and decomposition

Coarea formula

$$\|\nabla f\|_{L^1(\mathbb{R}^n)} = \int_{\mathbb{R}} \mathcal{H}^{n-1}(\partial\{x \in \mathbb{R}^n : f(x) > \lambda\})\, \mathrm{d}\lambda$$

Superlevel sets

$$\{\mathrm{M}f > \lambda\} = \{x \in \mathbb{R}^n : \mathrm{M}f(x) > \lambda\} = \bigcup \{B : f_B > \lambda\}$$

for *uncentered* maximal operators.

Decomposition of the boundary

Denote

$$\mathcal{B}_\lambda^{<} = \{B : f_B > \lambda,\ \mathcal{L}(B \cap \{f > \lambda\}) < 2^{-n-1}\mathcal{L}(B)\}$$

and $\mathcal{B}_\lambda^{\geq}$ accordingly.

Introduction: Tools

1. **relative isoperimetric inequality**:

$$\min\{\mathcal{L}(Q \cap E), \mathcal{L}(Q \setminus E)\}^{n-1} \lesssim_n \mathcal{H}^{n-1}(Q \cap \partial E)^n.$$

2. **Vitaly covering** and similar: general balls $\to$ separated balls
3. **Besicovitch covering for boundary**
4. **superlevelset estimate**: $f < 0$ on most of $B \Rightarrow$ most mass of f lies far above f_B

used in proof	isoperimetric, Vitali	boundary Besicovitch	superlevel
dyadic char. f.	**x**		
char. f.	**x**	**x**	
dyadic	**x**		**x**
fractional	**x**		**x**
cube	**x**	**x**	**x**

Proof: Reformulation and decomposition

We have

$$\{\mathrm{M}f > \lambda\} = \bigcup \mathcal{B}_\lambda^{<} \cup \bigcup \mathcal{B}_\lambda^{\geq}.$$

Since $\{f > \lambda\} \subset \{\mathrm{M}f > \lambda\}$ we have

$$\partial\{\mathrm{M}f > \lambda\} \subset (\partial\{\mathrm{M}f > \lambda\} \setminus \overline{\{f > \lambda\}}) \cup \partial\{f > \lambda\}.$$

We conclude

Decomposition

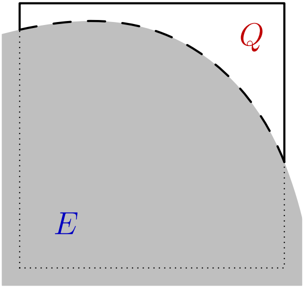
$$\begin{aligned}\int_{\mathbb{R}^d} |\nabla \mathrm{M}f| \leq \int_0^\infty \mathcal{H}^{n-1}\Big(\partial \bigcup \mathcal{B}_\lambda^{\geq} \setminus \overline{\{f > \lambda\}}\Big)\,\mathrm{d}\lambda \\ + \int_0^\infty \mathcal{H}^{n-1}\Big(\partial \bigcup \mathcal{B}_\lambda^{<}\Big)\,\mathrm{d}\lambda \\ + \int_{\mathbb{R}^d} |\nabla f|\end{aligned}$$

Proof: High density case $\mathcal{B}_\lambda^{\geq}$

Proposition

For Q, E with $\mathcal{L}(Q \cap E) \geq 2^{-n-1}\mathcal{L}(Q)$ we have

$$\mathcal{H}^{n-1}(\partial Q \setminus \overline{E}) \lesssim_n \mathcal{H}^{n-1}(Q \cap \partial E)$$



dyadic maximal operator

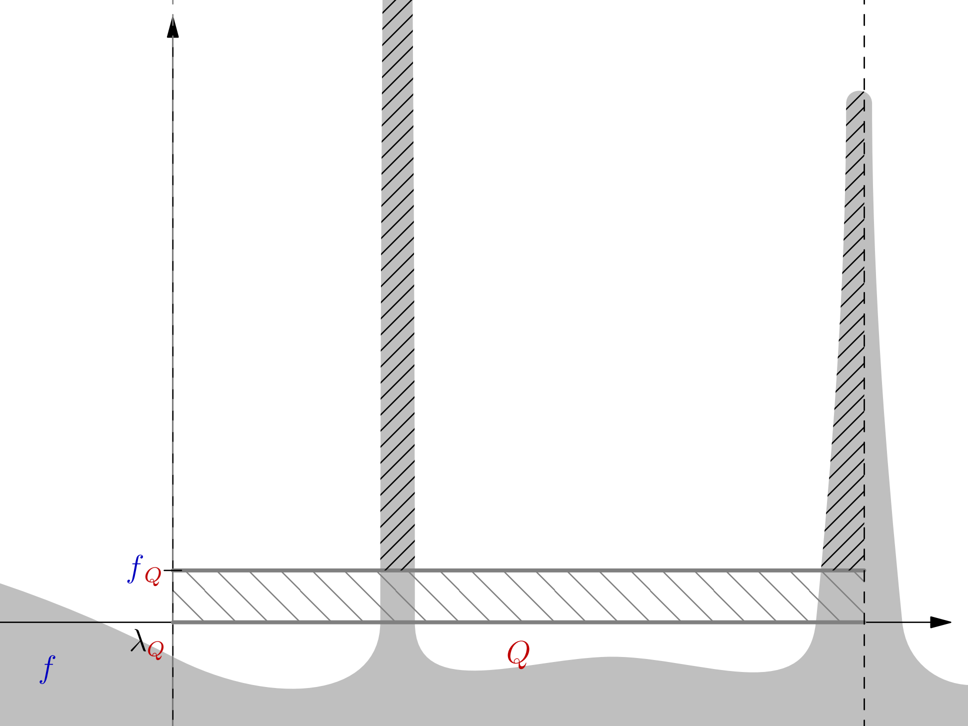
$$\mathrm{M}^{\mathrm{d}} f(x) = \sup_{\text{dyadic } Q,\ Q \ni x} f_Q.$$

$$\begin{aligned}
\mathcal{H}^{n-1}(\partial \bigcup \mathcal{Q}_\lambda^{\geq} \setminus \overline{\{f > \lambda\}}) &\leq \sum_{Q \in \mathcal{Q}_\lambda^{\geq}} \mathcal{H}^{n-1}(\partial Q \setminus \overline{\{f > \lambda\}}) \\
&\lesssim_n \sum_{Q \in \mathcal{Q}_\lambda^{\geq}} \mathcal{H}^{n-1}(Q \cap \partial\{f > \lambda\}) \\
&\leq \mathcal{H}^{n-1}(\partial\{f > \lambda\})
\end{aligned}$$

Proposition

For a set $\mathcal{B}$ of balls B with $\mathcal{L}(B \cap E) \geq 2^{-n-1}\mathcal{L}(B)$ we have

$$\mathcal{H}^{n-1}\Big(\partial \bigcup \mathcal{B} \setminus \overline{E}\Big) \lesssim_n \mathcal{H}^{n-1}\Big(\bigcup \mathcal{B} \cap \partial E\Big).$$



f_Q
λ_Q
f
Q

Proof: Low density case $\mathcal{B}_\lambda^<$, dyadic

$$\int_{\mathbb{R}} \mathcal{H}^{n-1}(\partial \bigcup \mathcal{Q}_\lambda^<)\,\mathrm{d}\lambda \leq \sum_{Q \text{ dyadic}} (f_Q - \lambda_Q)\mathcal{H}^{n-1}(\partial Q)$$

with

$$\mathcal{L}(Q \cap \{f > \lambda_Q\}) = 2^{-n-1}\mathcal{L}(Q)$$

Proposition

$$(f_Q - \lambda_Q)\mathcal{L}(Q) \lesssim_n \int_{f_Q}^{\infty} \mathcal{L}(Q \cap \{f > \lambda\}) \qquad \mathrm{d}\lambda$$

Proof: Low density case $\mathcal{B}_\lambda^<$, dyadic

$$\int_{\mathbb{R}} \mathcal{H}^{n-1}(\partial \bigcup \mathcal{Q}_\lambda^<)\,\mathrm{d}\lambda \le \sum_{Q \text{ dyadic}} (f_Q - \lambda_Q)\mathcal{H}^{n-1}(\partial Q)$$

with

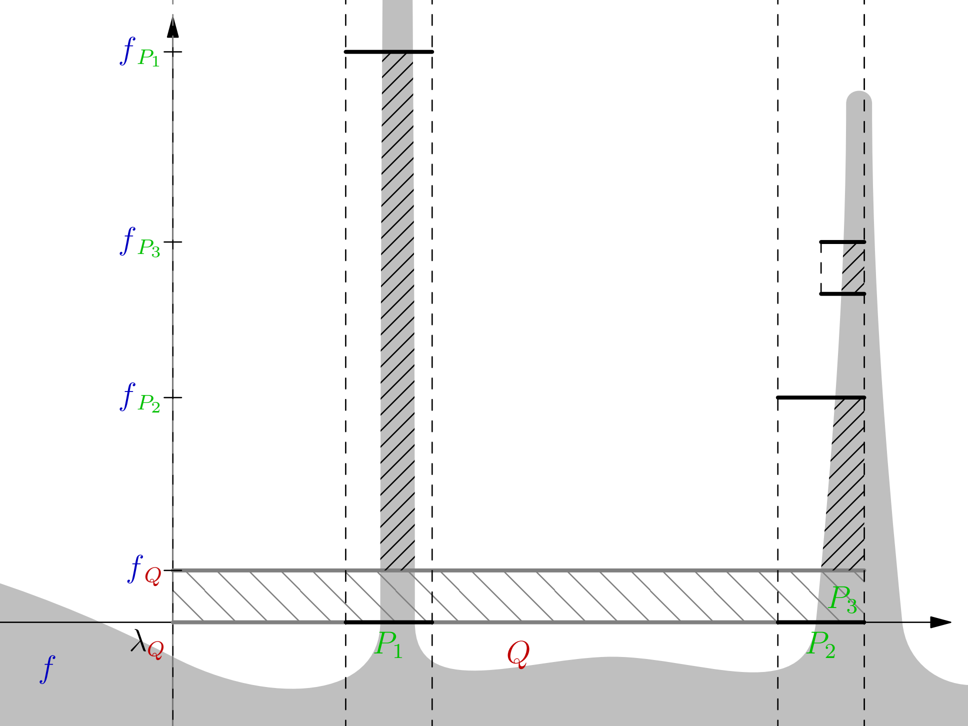
$$\mathcal{L}(Q \cap \{f > \lambda_Q\}) = 2^{-n-1}\mathcal{L}(Q)$$

Proposition

$$(f_Q - \lambda_Q)\mathcal{L}(Q) \lesssim_n \int_{f_Q}^{\infty} \sum_{P \subsetneq Q : \bar{\lambda}_P < \lambda < f_P} \mathcal{L}(P \cap \{f > \lambda\})\,\mathrm{d}\lambda$$

where P is maximal above $\bar{\lambda}_P$ and

$$\mathcal{L}(P \cap \{f > \bar{\lambda}_P\}) = 2^{-1}\mathcal{L}(P)$$



f_{P_1}
f_{P_3}
f_{P_2}
f_Q
λ_Q
f
P_1
Q
P_2
P_3

Proof: Low density case $\mathcal{B}_\lambda^<$, dyadic

Combining, we obtain

$$\int_{\mathbb{R}} \mathcal{H}^{n-1}(\partial \bigcup \mathcal{Q}_\lambda^<)\,\mathrm{d}\lambda$$
$$\lesssim_n \int_{\mathbb{R}} \sum_{Q \text{ dyadic}} \sum_{P \subsetneq Q : \bar{\lambda}_P < \lambda < f_P} \frac{\mathcal{L}(P \cap \{f > \lambda\})}{\mathrm{l}(Q)}\,\mathrm{d}\lambda$$

1. change the order of summation
2. convergence of the geometric sum
3. apply the relative isoperimetric inequality to P.
4. coarea formula to recover $\|\nabla f\|_1$

Proof: Low density case $\mathcal{B}_\lambda^<$, fractional

$1 \leq \alpha$ [Kinnunen + Saksman, Carneiro + Madrid]

$$\|\nabla \mathrm{M}_\alpha f\|_{\frac{n}{n-\alpha}} \lesssim_n \|\mathrm{M}_{\alpha-1} f\|_{\frac{n}{n-\alpha}} \lesssim_n \|f\|_{\frac{n}{n-1}} \lesssim_n \|\nabla f\|_1.$$

$0 < \alpha$

$$\|\nabla \mathrm{M}_\alpha f\|_{\frac{n}{n-\alpha}} \lesssim_n \|\mathrm{M}_{\alpha,-1} f\|_{\frac{n}{n-\alpha}} \lesssim_{n,\alpha} \|\nabla f\|_1,$$

$\mathrm{M}_{\alpha,-1}$ replacement for $\mathrm{M}_{\alpha-1}$ if $0 < \alpha < 1$.
Can bound $\mathrm{M}_{\alpha,-1} f$ both centered and uncentered

- using low density arguments from the dyadic proof
- extra flexibility coming from $\alpha > 0$, allowing for rough Vitali covering arguments

Proof: Low density case $\mathcal{B}_\lambda^<$, general cubes

cube maximal function

$$\mathrm{M}f(x) = \sup_{\text{cube } Q,\ Q \ni x} f_Q .$$

We reduce to almost dyadic cubes, using

Proposition (Vitali/Besicovitch for perimeter)

For any (finite) set of cubes $\mathcal{Q}$ there is a subset $\mathcal{S} \subset \mathcal{Q}$ of disjoint cubes such that

$$\mathcal{H}^{n-1}\Big(\partial \bigcup \mathcal{Q}\Big) \lesssim_n \sum_{S \in \mathcal{S}} \mathcal{H}^{n-1}(\partial S).$$

Uncentered HL $\widetilde{\mathrm{M}}f$ (balls)?

- All arguments work
- except low density bound $(f_B - \lambda_B)\mathcal{L}(B) \lesssim_n$?

Thank you