Appendix A
Proof of Theorem 2.8

Definition A.1. For $k \in \mathbb{Z}$ let $\mathcal{Q}_k$ be the collection of cubes in $\mathbb{R}^n$ which are congruent to $[0, 2^{-k})^n$ and whose vertices lie on the lattice $(2^{-k}\mathbb{Z})^n$.

The cubes in

$$\mathcal{Q}^* = \bigcup_{k \in \mathbb{Z}} \mathcal{Q}_k \tag{A.1}$$

are called the *dyadic* cubes.

A.4 Proof of Theorem 2.8

As it was mentioned after the statement of Theorem 2.8 it suffices to show that the operator T_m is of weak type (1,1), that is, there exists $c_1 > 0$ such that for every $f \in L^1(\mathbb{R}^n)$

$$\sup_{\alpha>0} \alpha \, |\{x \in \mathbb{R}^n \ : \ |T_m f(x)| > \alpha\}| \leq c_1 \, \|f\|_1. \tag{A.2}$$

To establish (A.2) we need the Calderón–Zygmund decomposition of L^1-functions.

Lemma A.1 (Calderón–Zygmund lemma). *Let $f \in L^1(\mathbb{R}^n)$. For any $\alpha > 0$, f can be decomposed as*

$$f = g + b = g + \sum_{j=1}^{\infty} b_j \tag{A.3}$$

such that

$$|g(x)| \leq 2^n \alpha \quad a.e \quad x \in \mathbb{R}^n, \tag{A.4}$$

$$b_j \text{ supported in } \overline{Q}_j, \ Q_j \text{ a dyadic cube with } \int_{Q_j} b_j \, dx = 0, \tag{A.5}$$

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$$\textit{the } Q_j's \textit{ are disjoint,} \quad \sum_{j=1}^{\infty} |Q_j| \le \alpha^{-1} \, \|f\|_1, \tag{A.6}$$

and

$$\|g\|_1 + \sum_{j=1}^{\infty} \|b_j\|_1 \le 6 \, \|f\|_1. \tag{A.7}$$

Proof. Assume $f \ge 0$ (otherwise $f = f^+ - f^-$ and decompose each part). Since $f \in L^1(\mathbb{R}^n)$ there exists l such that $|Q|^{-1} \int_Q f \, dy < \alpha$ for any cube of side length l.

Fix $k_0 \in \mathbb{Z}$ such that

$$2^{k_0 n} \, \|f\|_1 < \alpha.$$

We start with the family of cubes in $\mathcal{Q}_{k_0}$. Let Q^0 be one of them. Divide each side of Q^0 in two to get 2^n new dyadic cubes of side length $2^{-(k_0+1)}$. Let Q^1 be such a cube; there are two possibilities:

$$\text{(a)} \ \frac{1}{|Q^1|} \int_{Q^1} f \, dy < \alpha \quad \text{or} \quad \text{(b)} \ \frac{1}{|Q^1|} \int_{Q^1} f \, dy \ge \alpha.$$

In case (b) one stops the subdivision, noticing that

$$\alpha \le \frac{1}{|Q^1|} \int_{Q^1} f \, dy \le \frac{2^n}{|Q^0|} \int_{Q^0} f \, dy \le 2^n \alpha, \tag{A.8}$$

and collecting it in a sequence Q_j.

In case (a) the subdivision process continues. Thus, if $x \notin \bigcup_j Q_j$ it follows from the Lebesgue differentiation theorem (Exercise 2.6 (ii)) that

$$f(x) \le \alpha \text{ a.e. } x \in \mathbb{R}^n \setminus \cup_j Q_j. \tag{A.9}$$

Finally, we define

$$g(x) = \begin{cases} \dfrac{1}{|Q_j|} \displaystyle\int_{Q_j} f \, dy \ \text{ if } x \in Q_j, \\ \\ f(x) \ \text{ if } x \notin Q_j, \end{cases} \tag{A.10}$$

and

$$b_j(x) = (f(x) - g(x)) \chi_{Q_j}(x), \quad j \in \mathbb{Z}^+, \tag{A.11}$$

which yields the result. □

We shall denote by Q_j^* the cube having the same center as Q_j and twice its side length as

$$\Omega = \underset{j}{\cup} Q_j \text{ and } \Omega^* = \underset{j}{\cup} Q_j^* \tag{A.12}$$

with

$$|\Omega^*| \le \sum_j |Q_j^*| = 2^n \sum_j |Q_j|. \tag{A.13}$$

Proof of inequality (A.2). First we notice that using Calderón–Zygmund lemma

$$\begin{aligned} &|\{x \in \mathbb{R}^n \ : \ |T_m f(x)| > \alpha\}| \\ &\le |\{x \in \mathbb{R}^n \ : \ |T_m g(x)| > \alpha/2\}| + |\{x \in \mathbb{R}^n \ : \ |T_m b(x)| > \alpha/2\}| \qquad \text{(A.14)} \\ &\le |\{x \in \mathbb{R}^n \ : \ |T_m g(x)| > \alpha/2\}| + |\{x \notin \Omega^* \ : \ |T_m b(x)| > \alpha\}| + |\Omega^*| \\ &= E_1 + E_2 + E_3. \end{aligned}$$

From (A.13) and (A.6) in Calderón–Zygmung lemma we have that

$$E_3 = |\Omega^*| \le 2^n \sum_j |Q_j| \le 2^n \alpha^{-1} \|f\|_1. \tag{A.15}$$

Tchebychev's inequality and (A.4) in the Calderón–Zygmund lemma yield

$$\begin{aligned} E_1 \quad &= |\{x \in \mathbb{R}^n \ : \ |T_m g(x)| > \alpha/2\}| \le c \left(\frac{\|T_m g\|_2}{\alpha/2}\right)^2 \le c \, \frac{\|g\|_2^2}{\alpha^2} \\ &\le \frac{c}{\alpha^2} \|g\|_1 \, \|g\|_\infty \le \frac{c}{\alpha} \|g\|_1 \le \frac{c}{\alpha} \|f\|_1. \end{aligned} \tag{A.16}$$

Hence, it remains to prove that

$$E_2 = |\{x \notin \Omega^* \ : \ |T_m b(x)| > \alpha/2\}| \le c\alpha^{-1} \|f\|_1. \tag{A.17}$$

It will suffice to show that

$$\int\limits_{x \notin Q_j^*} |T_m b_j(x)| \, dx \le c\|b_j\|_1, \qquad j \in Z^+. \tag{A.18}$$

To establish (A.18) we follow the argument in [BeL].

Let $\varphi \in C_0^\infty(\{\xi \ : \ |\xi| < 2\})$, such that $\varphi(\xi) = 1$ for $|\xi| \le 1$. Let $\beta(\xi) = \varphi(\xi) - \varphi(2\xi)$. Thus

$$\sum_{l=-\infty}^{\infty} \beta(2^{-l}\xi) = 1 \quad \text{for } \ \xi \neq 0. \tag{A.19}$$

If $m_l(\xi) = \beta(\xi)\, m(2^l \xi)$, then by hypothesis (2.18)

$$\int |(1-\Delta)^{s/2} m_l(\xi)|^2 \, d\xi \, < c. \tag{A.20}$$

Thus, by Plancherel's identity using the notation $K_l(x) = \widehat{m}_l(x)$, one gets that

$$\int (1+|x|^2)^s |K_l(x)|^2 \, dx \, < c, \tag{A.21}$$

which, combined with the Cauchy–Schwarz inequality yields the estimate

$$\int\limits_{\{x:\, \max\limits_m |x_m|>R\}} |K_l(x)| \, dx \, < c\, R^{n/2-s}, \tag{A.22}$$

which is a good estimate for $R >> 1$.

Reapplying the estimates (A.20) and (A.21) for $\xi_k\, m_l(\xi)$ instead of $m_l(\xi)$ one finds that

$$\int |\nabla K_l(x)| \, dx \, < c. \tag{A.23}$$

Consequently, it follows that

$$\int |K_l(x+y) - K_l(x)| \, dx \, < c|y|. \tag{A.24}$$

We observe that as a temperate distribution,

$$K(x) = \sum_{l=-\infty}^{\infty} 2^{nl} K_l(2^l x) = \sum_{l=-\infty}^{\infty} \widehat{m}_l(2^{-l} x). \tag{A.25}$$

Assume that Q_j is a cube of side R centered at the origin. From (A.22) one has that

$$\begin{aligned} \int\limits_{x \notin Q_j^*} |2^{nl} K_l(2^l \cdot) * b_j| \, dx &\le \int\limits_{Q_j} \int\limits_{x \notin Q_j^*} |2^{nl} K_l(2^l(x-y))||b_j(y)| \, dx dy \\ &\le \|b_j\|_1 \int\limits_{\{x:\, \max\limits_m |x_m| \ge 2^l R\}} |K_l(x)| \, dx \\ &\le c\,(2^l R)^{n/2-s} \, \|b_j\|_1. \end{aligned} \tag{A.26}$$

Now using that $\int\limits_{Q_j} b_j dy = 0$ it follows that

$$\int\limits_{x \notin Q_j^*} 2^{nl} \int\limits_{y \in Q_j} K_l(2^l(x-y)) b_j(y) \, dy dx \tag{A.27}$$

$$= \int_{x \notin Q_j^*} 2^{nl} \int_{y \in Q_j} \big(K_l(2^l(x-y)) - K_l(2^l x)\big)\, b_j(y)\, dy dx.$$

Therefore, (A.24) yields

$$\int_{x \notin Q_j^*} |2^{nl} K_l(2^{nl}\cdot) * b_j|\, dx$$

$$\leq \int_{y \in Q_j} \int_{x \notin Q_j^*} 2^{nl} |K_l(2^l(x-y)) - K_l(2^l x)||b_j(y)|\, dx dy \tag{A.28}$$

$$\leq c\,(2^l R) \|b_j\|_1.$$

Adding in l in (A.26) for $2^l R > 1$ and in (A.28) for $2^l R \leq 1$ one gets that

$$\int_{x \notin Q_j^*} |T_m\, b_j(x)|\, dx \leq c\, \|b_j\|_1, \tag{A.29}$$

which completes the proof. □

Appendix B
Proof of Lemma 4.2

B.1 Proof of Lemma 4.2

Let

$$\Omega = \{(x,y) \in [0,1] \times [0,1] \mid x < y\} = \bigcup_j Q_j, \tag{B.1}$$

and

$$\mathcal{A} \equiv \{Q_j\}_j \tag{B.2}$$

where the Q_j's are disjoint dyadic cubes (see Definition A.1) such that if $\bar{Q}_j = \bar{I}_j \times \bar{J}_j$, ($I_j, J_j$ intervals), then

(i) $\#\,(\bar{Q}_j \cap \{(x,x) \mid x \in [0,1]\}) = 1.$
(ii) $\#\,\{Q_j \subseteq \Omega \mid \text{length side of } Q_j = 2^{-k}\} = 2^{k-1},\ k \in \mathbb{Z}^+.$

Without loss of generality assume $\|f\|_r = 1$ and define

$$F(t) = \int_{-\infty}^{t} |f(s)|^r\,ds, \tag{B.3}$$

so $F : \mathbb{R} \to [0,1]$ is a nondecreasing continuous function.

Notice that if $s < t$, then either

$$F(s) < F(t)$$

or

$$f \equiv 0, \quad \text{a.e. in}[s,t].$$

For $I = [a,b] \subseteq [0,1]$ one has that

$$F^{-1}([a,b]) = [A,B] \quad \text{with} \quad F(A) = a \quad \text{and} \quad F(B) = b. \tag{B.4}$$

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Hence

$$\int_A^B |f(s)|^r\, ds = F(B) - F(A) = b - a, \tag{B.5}$$

and

$$\|f\|_{L^r(F^{-1}(I))} = |I|^{1/r}. \tag{B.6}$$

Defining

$$B(f,g) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} K(t,s) f(s) g(t)\, ds dt \tag{B.7}$$

and

$$\tilde{B}(f,g) = \int\int_{s<t} K(t,s) f(s) g(t)\, ds dt \tag{B.8}$$

it will suffices to see that there exists $c > 0$ such that

$$|\tilde{B}(f,g)| \le c\, \|f\|_r \|g\|_{l'}, \qquad \frac{1}{l} + \frac{1}{l'} = 1. \tag{B.9}$$

We take $\|f\|_r = \|g\|_{l'} = 1$, thus

$$\begin{aligned} |\tilde{B}(f,g)| &= |\int\int_{s<t} K(t,s) f(s) g(t)\, ds dt| \\ &= \Big| \sum_{\substack{Q_j = I_j \times J_j \\ Q_j \in \mathcal{A}}} B(\chi_{F^{-1}(I_j)} f, \chi_{F^{-1}(J_j)} g)\Big| \\ &\le \sum_{Q_j \in \mathcal{A}} c\, \|f\|_{L^r(F^{-1}(I_j))} \|g\|_{L^{l'}(F^{-1}(J_j))} \\ &\le c \sum_{k \in \mathbb{Z}^+} (2^{-k})^{1/r} \sum_{|J_j| = 2^{-k}} \|g\|_{L^{l'}(F^{-1}(J_j))} \\ &\le c \sum_{k \in \mathbb{Z}^+} (2^{-k})^{1/r} \|g\|_{l'} \Big(\sum_{|J_j| = 2^{-k}} 1\Big)^{1/l} \\ &\le c \sum_{k \in \mathbb{Z}^+} (2^{-k})^{1/r} (2^{k-1})^{1/l}. \end{aligned} \tag{B.10}$$

Since by hypotheses $-\frac{1}{r} + \frac{1}{l} < 0$, this finishes the proof. □

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