CLASSICAL FOURIER ANALYSIS: INTERPOLATION OF L^p SPACES

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DEFINITION 1.1. *Let (X,μ) and (Y,ν) be measure spaces. Further let T be an operator defined on a linear space of complex-valued measurable functions on X and taking values in the set of all complex-valued, finite almost everywhere, measurable functions on Y. Then T is called* linear *if for all functions f and g in the domain of T and all $z \in \mathbb{C}$*

$$T(f+g) = T(f) + T(g) \qquad T(zf) = zT(f)$$

holds and quasi-linear *if*

$$|T(f+g)| \leqslant K\left(|T(f)| + |T(g)|\right) \qquad |T(zf)| = |z|\,|T(f)|$$

holds for some constant $K > 0$. If $K = 1$, T is called sublinear.

A complex-valued function f is said to be *holomorphic* in $\Omega \subseteq \mathbb{C}$ open, if $f'(z)$ exists for any $z \in \Omega$. By a region we shall mean a nonempty connected open subset of the complex plane. The proof of Hadamard's three lines lemma heavily relies on a restatement of the maximum modulus theorem (see [Rud87, p. 212]) found in [Rud87, p. 253].

THEOREM. *Let $\Omega \subseteq \mathbb{C}$ be a bounded region and f be a continuous function on $\overline{\Omega}$ which is holomorphic in Ω. Then*

$$|f(z)| \leqslant \sup\{|f(z)| : z \in \partial\Omega\}$$

for every $z \in \Omega$. If equality holds at one point $z \in \Omega$, then f is constant.

LEMMA 1.1. (Hadamard's three lines lemma) *Let F be a holomorphic function in the strip $S := \{z \in \mathbb{C} : 0 < \operatorname{Re} z < 1\}$, continuous and bounded on $\overline{S}$, such that $|F(z)| \leqslant B_0$ when $\operatorname{Re} z = 0$ and $|F(z)| \leqslant B_1$ when $\operatorname{Re} z = 1$, for some $0 < B_0, B_1 < \infty$. Then $|F(z)| \leqslant B_0^{1-\theta} B_1^{\theta}$ when $\operatorname{Re} z = \theta$, for any $0 < \theta < 1$.*

Proof. For $z \in \overline{S}$ define

$$G(z) := \frac{F(z)}{B_0^{1-z} B_1^{z}} \qquad G_n(z) := G(z)e^{(z^2-1)/n},\ n \in \mathbb{N}_{>0}$$

$G(z)$ and $G_n(z)$ are holomorphic in S by

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$$G'(z) = \frac{F'(z) - F(z)\log(B_1/B_0)}{B_0^{1-z}B_1^z} \qquad G_n'(z) = G'(z)e^{\left(z^2-1\right)/n} + \frac{2}{n}zG_n(z)$$

and $e^z \neq 0$ for every $z \in \mathbb{C}$. Further, we have

$$\left|B_0^{1-z}B_1^z\right| = \left(B_0^{1-z}B_0^{1-\overline{z}}B_1^z B_1^{\overline{z}}\right)^{1/2} = B_0^{1-\operatorname{Re} z}B_1^{\operatorname{Re} z}$$

Consider $0 \leqslant \operatorname{Re} z \leqslant 1$ and $B_0 \geqslant 1$. Then $B_0^{1-\operatorname{Re} z} \geqslant 1$ and $B_0^{1-\operatorname{Re} z} \geqslant B_0$ in the case $B_0 < 1$. Similarily, $B_1^{\operatorname{Re} z} \geqslant 1$ if $B_1 \geqslant 1$ and $B_1^{\operatorname{Re} z} \leqslant B_1$ if $B_1 < 1$. Hence

$$\left|B_0^{1-z}B_1^z\right| \geqslant \min\{1, B_0\}\min\{1, B_1\} > 0 \tag{1}$$

for all $z \in \overline{S}$. Since F is bounded on $\overline{S}$, we have $|F(z)| \leqslant L$ for some $L > 0$ and all $z \in \overline{S}$. Thus by (1)

$$|G(z)| = \frac{|F(z)|}{\left|B_0^{1-z}B_1^z\right|} \leqslant \frac{L}{\min\{1, B_0\}\min\{1, B_1\}} =: M$$

for every $z \in \overline{S}$. Fix $n \in \mathbb{N}_{>0}$ and write $z := x + iy \in \overline{S}$. Then

$$|G_n(z)| \leqslant M\left(e^{\left(x^2+2ixy-y^2-1\right)/n}e^{\left(x^2-2ixy-y^2-1\right)/n}\right)^{1/2} = Me^{-y^2/n}e^{\left(x^2-1\right)/n} \leqslant Me^{-y^2/n}$$

for $0 \leqslant x \leqslant 1$. Thus

$$\lim_{y \to \pm\infty} \sup\{|G_n(z)| : 0 \leqslant x \leqslant 1\} = 0$$

by the pinching-principle. Hence there exist $C_0, C_1 \in \mathbb{R}$, such that

$$\sup\{|G_n(z)| : 0 \leqslant x \leqslant 1\} \leqslant 1$$

when $y > C_0$ or $y < C_1$. Letting

$$C(n) := \max\{|C_0| + 1, |C_1| + 1\}$$

we conclude $|G_n(z)| \leqslant 1$ for all $0 \leqslant x \leqslant 1$ when $|y| \geqslant C(n)$. Now consider the rectangle $R := (0,1) \times (-C(n), C(n))$. We have $|G_n(z)| \leqslant 1$ on the lines $[0,1] \times \{\pm C(n)\}$. By

$$|G_n(iy)| = \frac{|F(iy)|}{\left|B_0^{1-iy}B_1^{iy}\right|}e^{-\left(y^2+1\right)/n} \leqslant 1 \qquad |G_n(1+iy)| = \frac{|F(1+iy)|}{\left|B_0^{-iy}B_1^{1+iy}\right|}e^{-y^2/n} \leqslant 1$$

we have $|G_n(z)| \leqslant 1$ on the lines $\{0\} \times [-C(n), C(n)]$, $\{1\} \times [-C(n), C(n)]$. Thus $|G_n(z)| \leqslant 1$ on ∂R. Since $|G_n(z)|$ is continuous on $\overline{R}$, holomorphic in R and R is a bounded region, the maximum modulus theorem implies

$$|G_n(z)| \leqslant \sup\{|G_n(z)| : z \in \partial R\} \leqslant 1$$

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for every $z \in R$. Therefore $|G_n(z)| \leqslant 1$ on $\overline{R}$ and so $|G_n(z)| \leqslant 1$ on $\overline{S}$. Since inequalities are preserved by limits and the modulus is a continuous function, we have that $|G(z)| = \lim_{n\to\infty} |G_n(z)| \leqslant 1$ for $z \in \overline{S}$. We conclude by

$$|F(\theta + it)| = |G(\theta + it)| \left| B_0^{1-\theta-it} B_1^{\theta+it} \right| \leqslant B_0^{1-\theta} B_1^{\theta}$$

whenever $0 < \theta < 1$, $t \in \mathbb{R}$. □

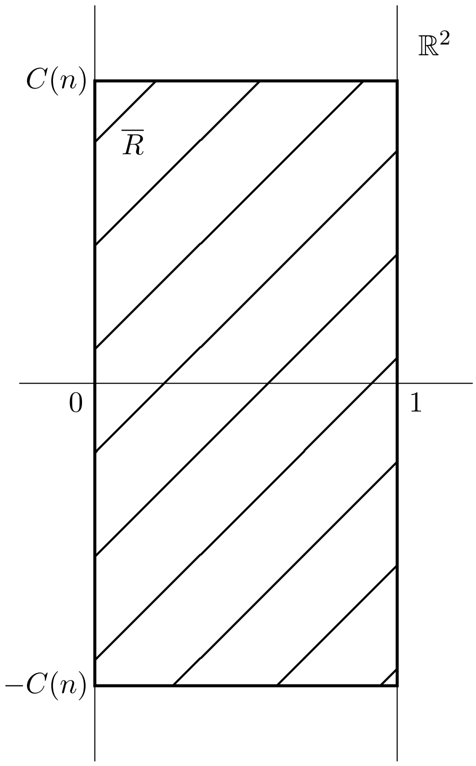

FIGURE 1. Sketch of the rectangle $\overline{R}$.

For two measure spaces (X, μ), (Y, ν) let Σ_X and Σ_Y denote the set of all finitely simple functions on X, Y respectively. The proof uses the following theorem found in [Fol99, p. 189].

THEOREM. *Let p, q be conjugate exponents. Suppose that g is a measurable function on X such that $fg \in L^1$ for all $f \in \Sigma_X$, and*

$$M_q(g) = \sup \left\{ \left| \int_X fg d\mu \right| : f \in \Sigma_X, \|f\|_{L^p} = 1 \right\} < \infty$$

Also, suppose either that $\{g \neq 0\}$ is σ-finite or that μ is semifinite. Then $g \in L^q$ and $M_q(g) = \|g\|_{L^q}$.

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Theorem 1.1. (Riesz-Thorin Interpolation Theorem) *Suppose that (X,μ), (Y,ν) are measure spaces and $1 \leqslant p_0, p_1, q_0, q_1 \leqslant \infty$. If $q_0 = q_1 = \infty$, suppose also that ν is semifinite. Let T be a linear operator defined on Σ_X and taking values in the set of measurable functions on Y, such that*

$$\|T(f)\|_{L^{q_0}} \leqslant M_0 \|f\|_{L^{p_0}} \qquad \|T(f)\|_{L^{q_1}} \leqslant M_1 \|f\|_{L^{p_1}} \tag{2}$$

for all $f \in \Sigma_X$ and $0 < M_0, M_1 < \infty$. Then for all $0 \leqslant \theta \leqslant 1$ we have

$$\|T(f)\|_{L^q} \leqslant M_0^{1-\theta} M_1^{\theta} \|f\|_{L^p} \tag{3}$$

for all $f \in \Sigma_X$, where

$$\frac{1}{p} = \frac{1-\theta}{p_0} + \frac{\theta}{p_1} \qquad \frac{1}{q} = \frac{1-\theta}{q_0} + \frac{\theta}{q_1}$$

Proof. If either $\theta = 0$ or $\theta = 1$, the estimate (3) follows directly from the hypotheses (2) on T. Thus we may assume $\underline{0 < \theta < 1}$. Furthermore, if $f \in \Sigma_X$, $\|f\|_{L^p} = 0$, then $f = 0$ μ-a.e. and either one of the hypotheses on T in (2) implies $T(f) = 0$ μ-a.e. and thus the estimate (3) holds trivially. Therefore we can assume $\underline{\|f\|_{L^p} \neq 0}$. Fix

$$f :\equiv \sum_{j=1}^{n} a_j e^{i\alpha_j} \chi_{A_j} \in \Sigma_X \qquad g :\equiv \sum_{k=1}^{m} b_k e^{i\beta_k} \chi_{B_k} \in \Sigma_Y$$

where $a_j, b_k > 0$ and $\alpha_j, \beta_k \in \mathbb{R}$ for every $j = 1, \dots, n$, $k = 1, \dots, m$ such that $\|g\|_{L^{q'}} \neq 0$ (recall $q' := q/(q-1)$). Define

$$P(z) := \frac{p}{p_0}(1-z) + \frac{p}{p_1} z \qquad Q(z) := \frac{q'}{q_0'}(1-z) + \frac{q'}{q_1'} z$$

for $z \in \mathbb{C}$ (since either $p = \infty$ implies $p_0 = p_1 = \infty$ or $q = 1$ implies $q_0 = q_1 = 1$, the functions P, Q are well-defined). Further let

$$f_z :\equiv \sum_{j=1}^{n} a_j^{P(z)} e^{i\alpha_j} \chi_{A_j} \qquad g_z :\equiv \sum_{k=1}^{m} b_k^{Q(z)} e^{i\beta_k} \chi_{B_k} \tag{4}$$

and

$$F(z) := \int_Y T(f_z) g_z \, d\nu \tag{5}$$

By the linearity of the operator T we have

$$F(z) = \sum_{j=1}^{n} \sum_{k=1}^{m} a_j^{P(z)} b_k^{Q(z)} e^{i\alpha_j} e^{i\beta_k} \int_Y T(\chi_{A_j}) \chi_{B_k} \, d\nu$$

and by Hölder's inequality

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$$
\begin{aligned}
\left|\int_Y T(\chi_{A_j})\chi_{B_k} d\nu\right| &\leqslant \int_Y \left|T(\chi_{A_j})\chi_{B_k}\right| d\nu \\
&= \left\|T(\chi_{A_j})\chi_{B_k}\right\|_{L^1} \\
&\leqslant \left\|T(\chi_{A_j})\right\|_{L^{q_0}} \left\|\chi_{B_k}\right\|_{L^{q_0'}} \\
&\leqslant M_0 \left\|\chi_{A_j}\right\|_{L^{p_0}} \left\|\chi_{B_k}\right\|_{L^{q_0'}} \\
&\leqslant M_0 \mu\left(A_j\right)^{1/p_0} \nu\left(B_k\right)^{1/q_0'}
\end{aligned} \tag{6}
$$

for each $j = 1, \dots, n$, $k = 1, \dots, m$ (even in the cases where either $p_0 = \infty$ or $q_0' = \infty$, or both, by observing that $\|\chi_A\|_{L^\infty} \leqslant 1$ for any measurable set A). Thus the function F is well-defined on $\mathbb{C}$. Let $t \in \mathbb{R}$. For $p, p_0 \neq \infty$

$$
\begin{aligned}
\|f_{it}\|_{L^{p_0}} &= \left(\sum_{j=1}^n \int_{A_j} |f_{it}|^{p_0}\, d\mu + \int_{X \setminus \bigcup_{j=1}^n A_j} |f_{it}|^{p_0}\, d\mu\right)^{1/p_0} \\
&= \left(\sum_{j=1}^n \left|a_j^{P(it)} e^{i\alpha_j}\right|^{p_0} \int_X \chi_{A_j} d\mu\right)^{1/p_0} \\
&= \left(\sum_{j=1}^n a_j^{p_0 \operatorname{Re} P(it)} \mu\left(A_j\right)\right)^{1/p_0} \\
&= \left(\sum_{j=1}^n a_j^p \mu\left(A_j\right)\right)^{p/(p_0 p)} \\
&= \|f\|_{L^p}^{p/p_0}
\end{aligned}
$$

holds. Let $p_0 = \infty$, $p \neq \infty$. Then $\|f_{it}\|_{L^\infty} = 1$ since $\left|a_j^{P(it)}\right| = a_j^{p/p_0} = 1$ and that there exists some index j, such that $\mu\left(A_j\right) \neq 0$. If $p = \infty$, then $p_0 = p_1 = \infty$ and thus $P(it) = 1$. By the same considerations we have $\|g_{it}\|_{L^{q_0'}} = \|g\|_{L^{q'}}^{q'/q_0'}$. Hence

$$
\begin{aligned}
|F(it)| &\leqslant \int_Y |T(f_{it}) g_{it}|\, d\nu \\
&= \|T(f_{it}) g_{it}\|_{L^1} \\
&\leqslant \|T(f_{it})\|_{L^{q_0}} \|g_{it}\|_{L^{q_0'}} \\
&\leqslant M_0 \|f_{it}\|_{L^{p_0}} \|g_{it}\|_{L^{q_0'}} \\
&= M_0 \|f\|_{L^p}^{p/p_0} \|g\|_{L^{q'}}^{q'/q_0'}
\end{aligned}
$$

by Hölder's inequality. In an analogous manner we derive

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$$\|f_{1+it}\|_{L^{p_1}} = \|f\|_{L^p}^{p/p_1} \qquad \|g_{1+it}\|_{L^{q_1'}} = \|g\|_{L^{q'}}^{q'/q_1'}$$

and thus

$$|F(1+it)| \leqslant M_1 \|f\|_{L^p}^{p/p_1} \|g\|_{L^{q'}}^{q'/q_1'}$$

Further by estimate (6)

$$\begin{aligned}
|F(z)| &\leqslant \sum_{j=1}^{n}\sum_{k=1}^{m} \left|a_j^{P(z)}\right| \left|b_k^{Q(z)}\right| \left|\int_Y T(\chi_{A_j})\chi_{B_k} d\nu\right| \\
&\leqslant M_0 \sum_{j=1}^{n}\sum_{k=1}^{m} a_j^{\operatorname{Re} P(z)} b_k^{\operatorname{Re} Q(z)} \mu(A_j)^{1/p_0} \nu(B_k)^{1/q_0'} \\
&\leqslant M_0 \sum_{j=1}^{n}\sum_{k=1}^{m} \max\left\{1, a_j^{p/p_0+p/p_1}\right\} \max\left\{1, b_k^{q'/q_0'+q'/q_1'}\right\} \mu(A_j)^{1/p_0} \nu(B_k)^{1/q_0'}
\end{aligned}$$

Hence F is bounded on $\overline{S}$ by some constant depending on f and g only. By

$$\begin{aligned}
F'(z) = &\sum_{j=1}^{n}\sum_{k=1}^{m} a_j^{P(z)} \log(a_j) \left(\frac{p}{p_1} - \frac{p}{p_0}\right) b_k^{Q(z)} e^{i\alpha_j} e^{i\beta_k} \int_Y T(\chi_{A_j})\chi_{B_k} d\nu \\
&+ \sum_{j=1}^{n}\sum_{k=1}^{m} a_j^{P(z)} b_k^{Q(z)} \log(b_k) \left(\frac{q'}{q_1'} - \frac{q'}{q_0'}\right) e^{i\alpha_j} e^{i\beta_k} \int_Y T(\chi_{A_j})\chi_{B_k} d\nu
\end{aligned}$$

it is immediate, that F is an entire function and thus holomorphic in S and continuous on $\overline{S}$. Therefore, Hadamard's three lines lemma yields

$$|F(z)| \leqslant \left(M_0 \|f\|_{L^p}^{p/p_0} \|g\|_{L^{q'}}^{q'/q_0'}\right)^{1-\theta} \left(M_1 \|f\|_{L^p}^{p/p_1} \|g\|_{L^{q'}}^{q'/q_1'}\right)^{\theta} = M_0^{1-\theta} M_1^{\theta} \|f\|_{L^p} \|g\|_{L^{q'}}$$

for $\operatorname{Re} z = \theta$, $0 < \theta < 1$. We have

$$\{T(f) \neq 0\} = \bigcup_{n=1}^{\infty} \{|T(f)| > 1/n\}$$

and by Chebychev's inequality either

$$\nu(\{|T(f)| > 1/n\}) \leqslant n^{q_0} \|T(f)\|_{L^{q_0}}^{q_0}$$

or

$$\nu(\{|T(f)| > 1/n\}) \leqslant n^{q_1} \|T(f)\|_{L^{q_1}}^{q_1}$$

whenever $q_0 \neq \infty$ or $q_1 \neq \infty$. Therefore, the set $\{T(f) \neq 0\}$ is σ-finite unless $q_0 = q_1 = \infty$. Further we have $P(\theta) = Q(\theta) = 1$. Thus by

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$$
\begin{aligned}
M_q\left(T(f)\right) &= \sup\left\{\left|\int_Y T(f) g d\nu\right| : g \in \Sigma_Y, \|g\|_{L^{q'}} = 1\right\} \\
&= \sup\left\{|F(\theta)| : g \in \Sigma_Y, \|g\|_{L^{q'}} = 1\right\} \\
&\leqslant M_0^{1-\theta} M_1^{\theta} \|f\|_{L^p}
\end{aligned}
$$

we conclude

$$
\|T(f)\|_{L^q} = M_q\left(T(f)\right) \leqslant M_0^{1-\theta} M_1^{\theta} \|f\|_{L^p}
$$

for any $f \in \Sigma_X$. □

Remark. *A more general version of the Riesz-Thorin interpolation theorem can be found in* [Fol99, pp. 200–202]. *There, a linear map*

$$
T : L^{p_0} + L^{p_1} \to L^{q_0} + L^{q_1}
$$

is considered. This follows using a density argument from the current version of the theorem and will not be prooven here.

Remark. *Using the previous remark, a standard application of the Riesz-Thorin interpolation theorem is to proove Young's inequality* [Gra14, pp. 22–23].

Lemma 1.2. (Hadamard's three lines lemma, extension) *Let F be a holomorphic function in the strip $S := \{z \in \mathbb{C} : 0 < \mathrm{Re} z < 1\}$ and continuous on $\overline{S}$, such that for some $0 < A < \infty$ and $\tau_0 \in (0, \pi)$ we have $\log|F(z)| \leqslant Ae^{\tau_0|\operatorname{Im} z|}$ for every $z \in \overline{S}$. Then*

$$
|F(z)| \leqslant \exp\left(\frac{\sin(\pi x)}{2}\int_{-\infty}^{\infty}\left[\frac{\log|F(it+iy)|}{\cosh(\pi t) - \cos(\pi x)} + \frac{\log|F(1+it+iy)|}{\cosh(\pi t) + \cos(\pi x)}\right] d\lambda(t)\right)
$$

whenever $z := x + iy \in S$.

Proof. Only a sketch will be given here. The core of the proof is the exploitation of the mapping

$$
h(z) := \frac{1}{\pi i}\log\left(i\frac{1+z}{1-z}\right)
$$

defined for $z \in \{z \in \mathbb{C} : |z| \leqslant 1\} \setminus \{\pm 1\}$ together with an application of a version of Fatou's lemma on the Poisson integral formula and the maximum principle for subharmonic functions. However, the main part of the proof is spent on a nice representation of the result obtained by the previous technical part. A change of variable is used to get the stated form of the upper bound. □

Definition 1.2. (Analytic family, admissible growth) *Let (X, μ), (Y, ν) be two σ-finite measure spaces and for every $z \in \overline{S}$ we have an associated linear operator T_z*

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which is defined on Σ_X and taking values in the space of all measurable functions on Y such that

$$\int_Y |T_z(\chi_A)\chi_B|\, d\nu < \infty$$

whenever $\mu(A), \nu(B) < \infty$. The family $(T_z)_{z\in\overline{S}}$ is said to be analytic *if for all $f \in \Sigma_X$, $g \in \Sigma_Y$ we have that*

$$z \mapsto \int_Y T_z(f) g d\nu$$

is analytic in S and continuous on $\overline{S}$. Further, an analytic family $(T_z)_{z\in\overline{S}}$ is called of admissible growth, *if there is a constant $\tau_0 \in (0, \pi)$, such that for all $f \in \Sigma_X$, $g \in \Sigma_Y$ a constant $0 < C(f, g) < \infty$ exists with*

$$\log \left| \int_Y T_z(f) g d\nu \right| \leqslant C(f, g) e^{\tau_0 |\operatorname{Im} z|}$$

for all $z \in \overline{S}$.

Theorem 1.2. (Stein's Theorem on Interpolation of Analytic Families of Operators) *Let $(T_z)_{z\in\overline{S}}$ be an analytic family of admissible growth, $1 \leqslant p_0, p_1, q_0, q_1 \leqslant \infty$ and suppose that M_0, M_1 are positive functions on the real line such that for some $\tau_1 \in (0, \pi)$*

$$\sup\left\{e^{-\tau_1|y|}\log M_0(y) : y \in \mathbb{R}\right\} < \infty \qquad \sup\left\{e^{-\tau_1|y|}\log M_1(y) : y \in \mathbb{R}\right\} < \infty \tag{7}$$

Fix $0 < \theta < 1$ and define

$$\frac{1}{p} := \frac{1-\theta}{p_0} + \frac{\theta}{p_1} \qquad \frac{1}{q} := \frac{1-\theta}{q_0} + \frac{\theta}{q_1} \tag{8}$$

Further suppose that for all $f \in \Sigma_X$ and $y \in \mathbb{R}$ we have

$$\|T_{iy}(f)\|_{L^{q_0}} \leqslant M_0(y)\|f\|_{L^{p_0}} \qquad \|T_{1+iy}(f)\|_{L^{q_1}} \leqslant M_1(y)\|f\|_{L^{p_1}} \tag{9}$$

Then for all $f \in \Sigma_X$ we have

$$\|T_\theta(f)\|_{L^q} \leqslant M(\theta)\|f\|_{L^p}$$

where for $0 < x < 1$

$$M(x) = \exp\left(\frac{\sin(\pi x)}{2}\int_{-\infty}^{\infty}\left[\frac{\log M_0(t)}{\cosh(\pi t) - \cos(\pi x)} + \frac{\log M_1(t)}{\cosh(\pi t) + \cos(\pi x)}\right] d\lambda(t)\right)$$

Proof. As mentioned in Terence Tao's blog, Fefferman once noted, that this proof can be obtained from that of the Riesz-Thorin theorem 1.1 simply by adding a single letter of

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the alphabet. Indeed, this is truly the case, since all hypotheses made in the theorem incorporate the same proof as in the Riesz-Thorin theorem. The only heavy and technical part is the proof of the extension of Hadamard's three lines lemma 1.2. □

THEOREM 1.3. (The Marcinkiewicz Interpolation Theorem) *Let* (X, μ) *be a* σ*-finite measure space,* (Y, ν) *another measure space and* $0 < p_0 < p_1 \leqslant \infty$*. Further let* T *be a sublinear operator defined on*

$$L^{p_0} + L^{p_1} := \{f_0 + f_1 : f_0 \in L^{p_0}(X, \mu), f_1 \in L^{p_1}(X, \mu)\}$$

and taking values in the space of measurable functions on Y*. Assume that there exist* $0 < A_0, A_1 < \infty$ *such that*

$$\forall f \in L^{p_0}(X, \mu) \; \|T(f)\|_{L^{p_0,\infty}} \leqslant A_0 \|f\|_{L^{p_0}} \tag{10}$$

$$\forall f \in L^{p_1}(X, \mu) \; \|T(f)\|_{L^{p_1,\infty}} \leqslant A_1 \|f\|_{L^{p_1}} \tag{11}$$

Then for all $p_0 < p < p_1$ *and for all* $f \in L^p(X, \mu)$ *we have the estimate*

$$\|T(f)\|_{L^p} \leqslant A \, \|f\|_{L^p} \tag{12}$$

where

$$A := 2 \left(\frac{p}{p - p_0} + \frac{p}{p_1 - p} \right)^{1/p} A_0^{\frac{\frac{1}{p} - \frac{1}{p_1}}{\frac{1}{p_0} - \frac{1}{p_1}}} A_1^{\frac{\frac{1}{p_0} - \frac{1}{p}}{\frac{1}{p_0} - \frac{1}{p_1}}} \tag{13}$$

Proof. Again, only a sketch of the proof will be given here. The proof has the following structure.

(i.) $p_1 < \infty$.

a. Split f using the two cut-off functions

$$f_0(x; \alpha, \delta) := \begin{cases} f(x), & |f(x)| > \delta\alpha, \\ 0, & |f(x)| \leqslant \delta\alpha. \end{cases}$$

$$f_1(x; \alpha, \delta) := \begin{cases} f(x), & |f(x)| \leqslant \delta\alpha, \\ 0, & |f(x)\rangle \, \delta\alpha. \end{cases}$$

for some $\alpha, \delta > 0$.

b. Estimate the distribution function $d_{T(f)}$ at α using the sublinearity of T and the splitting obtained in **a.**.

c. Estimate $\|T(f)\|_{L^p}^p$ using the representation (see [Gra14, p. 5])

$$\|f\|_{L^p}^p = p \int_0^\infty \alpha^{p-1} d_f(\alpha) d\lambda(\alpha)$$

(ii.) $p_1 = \infty$.

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a. Using the same splitting as in part **(i.)** of the function f, we show that $\mu(\{|T(f_1)| > \alpha/2\}) = 0$.
b. Estimate the distribution function $d_{T(f_0)}$ at α.
c. Estimate $\|T(f)\|_{L^p}^p$ as in **(i.)** part **c.**.

$\square$