Yannis Bähni

Introduction to Functional Analysis

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Contents

Topological Spaces

1. Definitions and Basic Notions

1.1. Topologies.

Definition 1.1. *Let X be a set. A **topology** on X is a collection $\mathcal{T}$ of subsets of X satisfying the following properties:*

    (i) $\varnothing, X \in \mathcal{T}$.

    (ii) If $(U_\alpha)_{\alpha \in A}$ is a family of elements of $\mathcal{T}$, then $\bigcup_{\alpha \in A} U_\alpha \in \mathcal{T}$.

    (iii) If $U_1, \ldots, U_n \in \mathcal{T}$, then $U_1 \cap \cdots \cap U_n \in \mathcal{T}$.

*A set X for which a topology $\mathcal{T}$ has been specified is called a **topological space** and elements of $\mathcal{T}$ are called **open sets**.*

Example 1.1 (Topologies).

    (a) Let $(X, \mathcal{T})$ be a topological space and let $S \subseteq X$. Then the collection $\mathcal{T}_S := \{S \cap U : U \in \mathcal{T}\}$ is a topology on S, since $S = S \cap X \in \mathcal{T}_S$, $\varnothing = S \cap \varnothing \in \mathcal{T}_S$, for any family $(S \cap U_\alpha)_{\alpha \in A}$ we have $\bigcup_{\alpha \in A}(S \cap U_\alpha) = S \cap \bigcup_{\alpha \in A} U_\alpha \in \mathcal{T}_S$ and if $(S \cap U_1) \cap \cdots \cap (S \cap U_n) \in \mathcal{T}_S$ we have also $S \cap (U_1 \cap \cdots \cap U_n) \in \mathcal{T}_S$. The topology $\mathcal{T}_S$ on S is called the **subspace topology** and $(S, \mathcal{T}_S)$ is called a **subspace** of $(X, \mathcal{T})$.

Definition 1.2. *Let $(X, \mathcal{T})$ be a topological space and $A \subseteq X$. The **closure of A in X**, denoted by $\overline{A}$, is defined by*

$$\overline{A} := \bigcap \{B \subseteq X : A \subseteq B, B^c \in \mathcal{T}\}. \tag{1}$$

*The **interior of A in X**, denoted by $\operatorname{Int} A$, is defined by*

$$\operatorname{Int} A := \bigcup \{C \subseteq X : C \subseteq A, C \in \mathcal{T}\}. \tag{2}$$

There is an eminent characterization of a point being in the closure of a subset $A \subseteq X$ of a topological space X.

Proposition 1.1. *Let X be a topological space and $A \subseteq X$. Then $x \in \overline{A}$ if and only if the following condition holds: Every neighbourhood U of x contains a point belonging to A.*

PROOF. Assume that there exists a neighbourhood U of x such that $U \cap A = \varnothing$. Then U^c is closed and $A \subseteq U^c$. But $x \notin U^c$ and thus $x \notin \overline{A}$. Conversly, assume $x \notin \overline{A}$. Thus we find a closed set B such that $A \subseteq B$ and $x \notin B$. But then B^c is open and $B^c \cap A = \varnothing$. $\qquad\square$

1.2. Continuity and Convergence.

Definition 1.3. *Let X and Y be two topological spaces and $f : X \to Y$. The map f is said to be **continuous** if for any open set $U \subseteq Y$ we have that $f^{-1}(Y)$ is open in X.*

Exercise 1.1. Prove that a mapping $f : X \to Y$ between two topological spaces X and Y is continuous if and only if for all $A \subseteq Y$ closed, $f^{-1}(Y)$ is closed in X. *Hint:* Use that for $A, B \subseteq Y$ we have $f^{-1}(A \setminus B) = f^{-1}(A) \setminus f^{-1}(B)$.

Definition 1.4. *Let X be a topological space, $(x_n)_{n\in\mathbb{N}}$ be a sequence in X and $x \in X$. The sequence $(x_n)_{n\in\mathbb{N}}$ is said to **converge to x** if for every neighbourhood U of x there exists $N \in \mathbb{N}$ such that $x_n \in U$ for any $n > N$.*

Corollary 1.1. *Let X be a topological space and $A \subseteq X$. If $(x_n)_{n\in\mathbb{N}}$ is a convergent sequence in A, i.e. $x_n \in A$ for any $n \in \mathbb{N}$, then its limit belongs to $\overline{A}$.*

PROOF. This is immediate by the characterization of proposition 1.1. $\square$

1.3. Connectedness and Compactness.

Definition 1.5. *Let X be a topological space. If $X = U \cup V$ for some disjoint open sets $U, V \neq \varnothing$, X is called **disconnected**, otherwise X is said to be **connected**.*

Definition 1.6. *Let X be a topological space. An **open cover** of X is a family $(U_\alpha)_{\alpha\in A}$ of open subsets of X such that $X = \bigcup_{\alpha\in A} U_\alpha$. A **subcover** of $(U_\alpha)_{\alpha\in A}$ is a subfamily $(U_\alpha)_{\alpha\in A'}$, $A' \subseteq A$.*

Definition 1.7. *A topological space X is said to be **compact** if any open cover has a finite subcover.*

Theorem 1.1 (Main Theorem on Compactness). *Let X and Y be topological spaces and $f : X \to Y$ be continuous. If X is compact, then $f(X)$ is compact.*

Proposition 1.2. *Every closed, bounded interval in $\mathbb{R}$ is compact.*

Theorem 1.2 (Extreme Value Theorem). *If X is a compact space and $f : X \to \mathbb{R}$ is continuous, then f is bounded and attains its maximum and minimum values on X.*

Exercises

2. Metric Spaces

We follow [Lee11, pp. 396 – 398].

Definition 2.1. *Let M be a set. A **metric** on M is a function*

$$d : M \times M \to \mathbb{R} \tag{3}$$

having the following properties:

   (i) $d(x,y) \geq 0$ for all $x,y \in M$.
   (ii) $d(x,y) = 0$ if and only if $x = y$.
   (iii) $d(x,y) = d(y,x)$ for all $x,y \in M$.
   (iv) (Triangle Inequality) $d(x,z) \leq d(x,y) + d(y,z)$ for all $x,y,z \in M$.

   *If on a set M a metric d has been specified, the tuple (M,d) is called a **metric space**.*

Definition 2.2. *Let (M,d) be a metric space. For any $x \in M$ and $r > 0$, the **open ball of radius r around x** is the set*

$$B_r(x) := \{y \in M : d(y,x) < r\}. \tag{4}$$

Proposition 2.1. *Let (M,d) be a metric space.*

   (a) The collection

$$\mathcal{T}_d := \{A \subseteq M : \forall x \in A \exists r > 0 \text{ such that } B_r(x) \subseteq A\} \tag{5}$$

   *is a topology on M, called the **metric topology induced by the metric d**.*
   (b) For each $x \in M$ and $r > 0$ we have $B_r(x) \in \mathcal{T}_d$.
   (c) $A \subseteq M$ is in $\mathcal{T}_d$ if and only if A can be written as a union of some open balls.

PROOF. First we prove (a). Obviously, $\varnothing, M \in \mathcal{T}_d$. Consider a family $(U_\alpha)_{\alpha \in A} \in \mathcal{T}_d$ and let $x \in \bigcup_{\alpha \in A} U_\alpha$. Thus $x \in U_\alpha$ for some $\alpha \in A$. Since $U_\alpha \in \mathcal{T}_d$, we find $r > 0$ such that $B_r(x) \subseteq U_\alpha$. Hence $B_r(x) \subseteq \bigcup_{\alpha \in A} U_\alpha$ and so $\bigcup_{\alpha \in A} U_\alpha \in \mathcal{T}_d$. Now assume $U_1, \ldots, U_n \in \mathcal{T}_d$ and let $x \in U_1 \cap \cdots \cap U_n$. Since each $U_i \in \mathcal{T}_d$, we find $r_i > 0$ such that $B_{r_i}(x) \subseteq U_i$ for each $i = 1, \ldots, n$. Setting $r := \min\{r_1, \ldots, r_n\}$ we have that $B_r(x) \subseteq U_1 \cap \cdots \cap U_n$ and thus $U_1 \cap \cdots \cap U_n \in \mathcal{T}_d$. To prove (b), let $y \in B_r(x)$. Then for $z \in B_{r-d(x,y)}(y)$ we have

$$d(x, z) \leq d(x, y) + d(y, z) < d(x, y) + r - d(x, y) = r \tag{6}$$

and hence $z \in B_r(x)$. To prove (c), let $A \in \mathcal{T}_d$. Then for any $x \in A$ we find r_x such that $B_{r_x}(x) \subseteq A$. But then $\bigcup_{x \in A} B_{r_x}(x) = A$. Conversely, assume $A = \bigcup_{\alpha \in A} B_{r_\alpha}(x_\alpha)$. By (b) we have that $B_{r_\alpha}(x_\alpha) \in \mathcal{T}_d$ for each $\alpha \in A$. Thus by (a) we have that $\bigcup_{\alpha \in A} B_{r_\alpha}(x_\alpha) \in \mathcal{T}_d$. $\square$

Proposition 2.2. *Let (M, d) and (M', d') be metric spaces and $f : M \to M'$. The mapping f is continuous if and only if the following condition holds: For any $x \in M$ and $\varepsilon > 0$ there exists a $\delta > 0$ such that $d(x, y) < \delta$ implies $d(f(x), f(y)) < \varepsilon$ for every $y \in M$.*

PROOF. Assume f is continuous. Let $x \in M$ and $\varepsilon > 0$. Then $f^{-1}(B_\varepsilon(f(x)))$ is open in M since f is continuous and thus we find $\delta > 0$ such that $B_\delta(x) \subseteq f^{-1}(B_\varepsilon(f(x)))$. Conversely, let $U \subseteq M'$ be open. For any $\square$

Proposition 2.3 (Sequence Criterion for Continuity). *Let (M, d) and (M', d') be metric spaces. A mapping $f : M \to M'$ is continuous if and only if the following criterion holds: If $(x_n)_{n \in \mathbb{N}}$ is a sequence in M which converges to some $x \in M$, then $\lim_{n \to \infty} f(x_n) = f(x)$.*

Definition 2.3. *Two metrics d and d' on a set M are said to be **equivalent** if $\mathcal{T}_d = \mathcal{T}_{d'}$.*

A useful criterion to determine wether two metrics d and d' are equivalent or not is stated in the following proposition.

Proposition 2.4. *Let d and d' be two metrics on a set M. Then d and d' are equivalent if and only if the following condition is satisfied: for every $x \in M$ and every $r > 0$ there exist $r_1, r_2 > 0$ such that $B_{r_1}^{(d')}(x) \subseteq B_r^{(d)}(x)$ and $B_{r_2}^{(d)}(x) \subseteq B_r^{(d')}(x)$.*

PROOF. Assume $\mathcal{T}_d = \mathcal{T}_{d'}$. Then it is obvious that the condition is satisfied with $r_1 = r_2 = r$. Conversely, assume $U \in \mathcal{T}_d$. $\square$

Definition 2.4. *Two metrics d and d' on a set M are said to be **strongly equivalent** if there are $c, c' > 0$ such that for all $x, y \in M$*

$$d(x, y) \leq c' d'(x, y) \qquad and \qquad d'(x, y) \leq c d(x, y). \tag{7}$$

Corollary 2.1. *Strongly equivalent metrics are equivalent.*

PROOF. This follows immediately from proposition 2.4 by setting $r_1 := r/c'$ and $r_2 := r/c$. $\square$

Exercises

Exercise 2.1. Let (M, d) be a metric space , $(x_n)_{n \in \mathbb{N}}$ a sequence in M and $x \in M$. The sequence $(x_n)_{n \in \mathbb{N}}$ converges to x if and only if the following condition is satisfied: For any $\varepsilon > 0$ there exists $N \in \mathbb{N}$ such that $d(x_n, x) < \varepsilon$ whenever $n > N$.

Exercise 2.2. Let (M, d) be a metric space and $(x_n)_{n \in \mathbb{N}}$. Then $\lim_{n \to \infty} x_n = x$ if and only if $\lim_{n \to \infty} d(x_n, x) = 0$, i.e. the sequence $(d(x_n, x))_{n \in \mathbb{N}}$ converges to zero in $(\mathbb{R}, |\cdot|)$.

Exercise 2.3. Prove proposition 2.3.

Exercise 2.4. Let M be a set. Show that equivalence of metrics on M is an equivalence relation on the set of all metrics on M.

Exercise 2.5. Let M be a set. Show that strong equivalence of metrics on M is an equivalence relation on the set of all metrics on M.

Exercise 2.6. Let X be a topological space. A subset of X is called an $\boldsymbol{F_\sigma}$-***set*** if it is a countable union of closed sets and a $\boldsymbol{G_\delta}$-***set*** if it is a countable intersection of open sets (see [OB98, p. 61]). Assume we are given a metric d on X. For a nonempty subset A of X we define the real valued ***distance function*** $\boldsymbol{\rho_A}$ by $\rho_A(x) := \inf\{d(x,a) : a \in A\}$ for any $x \in X$.

    (a) Show that ρ_A is continuous. *Hint:* Show that ρ_A is in fact Lipschitz continuous.
    (b) Show that $\rho_A^{-1}(\{0\}) = \overline{A}$. *Hint:* Use corollary 1.1.
    (c) Show that any closed subset of X is a G_δ-set.
    (d) Show that any open subset of X is an F_σ-set.

3. Normed Spaces

Definition 3.1. *Let X be a real or complex vector space. A mapping*

$$\|\cdot\| : X \to \mathbb{R} \tag{8}$$

is called ***norm***, *if*

    (i) $\|\lambda x\| = |\lambda| \, \|x\|$ *for all $\lambda \in \mathbb{C}$ and $x \in X$.*
    (ii) $\|x + y\| \le \|x\| + \|y\|$ *for all $x, y \in X$.*
    (iii) $\|x\| = 0$ *implies $x = 0$.*

    If only (i) and (ii) hold, $\|\cdot\|$ is called a ***seminorm***. *If a norm has been specified on a vector space X, the tuple $(X, \|\cdot\|)$ is called a* ***normed space***.

Definition 3.2. *Two norms $\|\cdot\|$ and $\|\|x\|\|$ are said to be* ***equivalent*** *if the induced metrics are strongly equivalent.*

There is a usefull result in the finite dimenisonal case (see [Wer11, p. 26]).

Theorem 3.1. *Let X be a finite dimensional real or complex vector space. Then any two norms are equivalent.*

PROOF. Let $\{e_1, \ldots, e_n\}$ be a basis of X, $x := \sum_{k=1}^n x_k e_k \in X$ and $\|\cdot\|$ be a norm on X. We show that $\|\cdot\|$ is equivalent to the euclidean norm. Hölder's inequality for series (see [Els11, p. 224]) yields

$$\|x\| \le \left(\sum_{k=1}^n |x_k|^2\right)^{1/2} \left(\sum_{k=1}^n \|e_k\|^2\right)^{1/2} \le \sqrt{n} \max\{\|e_1\|, \ldots, \|e_n\|\} \|x\|_2 \tag{9}$$

Let $(x_n)_{n \in \mathbb{N}}$ be a sequence in $(X, \|\cdot\|_2)$ which converges to $x \in X$. By estimate (9) and the reverse triangle inequality we get

$$0 \le \|\|x_n\| - \|x_n\|\| \le \|x_n - x\| \le \sqrt{n} \max\{\|e_1\|, \ldots, \|e_n\|\} \|x_n - x\|_2 \tag{10}$$

which implies by double application of exercise 2.2

$$\lim_{n \to \infty} \|x_n\| = \|x\|. \tag{11}$$

Hence $\|\cdot\|$ is a continuous function on $(X, \|\cdot\|_2)$. Furthermore, $\mathbb{S}^{n-1} = \|\cdot\|_2^{-1}(\{1\})$ and $\mathbb{S}^{n-1}$ is clearly bounded since $\mathbb{S}^{n-1} \subseteq \overline{B}_1(0)$. Therefore $\mathbb{S}^{n-1}$ is compact by Heine-Borel and by the extreme value theorem 1.2 we get that $\|\cdot\|$ attains its minimum value $\|x_0\|$ on $\mathbb{S}^{n-1}$. Since $\|\cdot\|$ is a norm, we must have $\|x_0\| > 0$ and since $x/\|x\|_2 \in \mathbb{S}^{n-1}$ for $x \ne 0$ we get

$$\|x_0\| \, \|x\|_2 \le \|x\|. \tag{12}$$

The case $x = 0$ holds trivially. $\qquad\square$

Exercises

Exercise 3.1. Show that if $\|\cdot\| : X \to \mathbb{R}$ is a norm, then $\|x\| \geq 0$ for any $x \in X$.

Exercise 3.2. Show that any norm $\|\cdot\|$ induces a metric $d_{\|\cdot\|}$ on X by setting $d_{\|\cdot\|}(x,y) :=$ $\|x - y\|$ for $x, y \in X$.

Exercise 3.3. Show that if $(X, \|\cdot\|)$ is a normed space, then the ***reverse triangle inequality*** $|\|x\| - \|y\|| \leq \|x - y\|$ holds for any $x, y \in X$. Deduce that $\|\cdot\|$ is a Lipschitz continuous function on $(X, \|\cdot\|)$.

L^p **Spaces**

1. Interpolation of L^p Spaces

1.1. The Lemma of I. I. Hirschman and Hadamard's Three Lines Lemma.

Lemma 1.1 (I. I. Hirschman). *Let F be a holomorphic function in the strip $S := \{z \in \mathbb{C} : 0 < \operatorname{Re} z < 1\}$ and continuous on $\overline{S}$, such that for some $0 < A < \infty$ and $0 \le \tau_0 < \pi$ we have $\log|F(z)| \le Ae^{\tau_0|\operatorname{Im} z|}$ for every $z \in \overline{S}$. Then*

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

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

PROOF. We will first prove the case $y = 0$. Assume F to be not identically zero (the case where F is identically zero is trivial). Let h be as in lemma (**??**) and let $\zeta := \rho e^{i\theta}$, $0 \le \rho < 1$. Since $\zeta \in D$, we have $0 < \operatorname{Re} h(\zeta) < 1$ and thus the hypothesis on F and lemma (**??**) yields

$$\log|F(h(\zeta))| \le Ae^{\frac{\tau_0}{\pi}|\log|(1+\zeta)/(1-\zeta)||} \le Ae^{\tau_0/\pi}\frac{1}{|\cos(\theta/2)|^{\tau_0/\pi}}\frac{1}{|\sin(\theta/2)|^{\tau_0/\pi}} \quad (13)$$

for $1/(2e-1) \le \rho$. Since $0 < \tau_0 < \pi$, inequality (13) asserts, that $\log|F(h(\zeta))|$ is bounded from above by an integrable function of θ, independently of $\rho \ge 1/(2e-1)$. Furthermore we have

$$M := \sup\left\{\log|F(h(\zeta))| : \zeta \in \overline{B}_{1/(2e-1)}\right\} < \infty \quad (14)$$

since a upper semicontinuous function on a compact space attains its supremum (see lemma **??**). Hence

$$\log|F(h(\rho e^{i\theta}))| \le \max\left\{M, Ae^{\tau_0/\pi}\frac{1}{|\cos(\theta/2)|^{\tau_0/\pi}}\frac{1}{|\sin(\theta/2)|^{\tau_0/\pi}}\right\} =: g(\theta) \quad (15)$$

for any $0 \le \rho < 1$ where $g \in L^1[-\pi, \pi]$. Let $0 \le \rho < R < 1$ and $a_1, \dots, a_n$ denote the zeros of $F(h(\zeta))$ for $|\zeta| < R$ (since $F \circ h$ is holomorphic for $|\zeta| < 1$ there are indeed only finitely many ones) multiple zeros being repeated. Then for $F(h(\zeta)) \ne 0$ we have by the *Poisson-Jensen formula* (see [Ahl79, p. 208])

$$\log|F(h(\zeta))| = -\sum_{k=1}^{n}\log\left|\frac{R^2 - \overline{a}_k\zeta}{R(\zeta - a_k)}\right| + \frac{1}{2\pi}\int_{-\pi}^{\pi}\operatorname{Re}\left[\frac{Re^{it} + \zeta}{Re^{it} - \zeta}\right]\log|F(h(Re^{it}))|\,\mathrm{d}t$$

$$(16)$$

Therefore by

$$\operatorname{Re}\left[\frac{Re^{it} + \zeta}{Re^{it} - \zeta}\right] = \operatorname{Re}\left[\frac{R^2 - 2i\operatorname{Im}\left[\zeta Re^{-it}\right] - |\zeta|^2}{R^2 - 2\operatorname{Re}\left[\zeta Re^{-it}\right] + |\zeta|^2}\right]$$

$$= \operatorname{Re}\left[\frac{R^2 - 2iR\rho\sin(\theta - t) - \rho^2}{R^2 - 2R\rho\cos(\theta - t) + \rho^2}\right]$$

$$= \frac{R^2 - \rho^2}{R^2 - 2R\rho\cos(\theta - t) + \rho^2}$$

and since $\left(R^2 - |a_k|^2\right)\left(R^2 - \rho^2\right) \geq 0$ for all $k = 1, \ldots, n$ implies $|R^2 - \overline{a}_k\zeta| \geq |R(\zeta - a_k)|$ the estimate

$$\log|F(h(\zeta))| \leq \frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{R^2 - \rho^2}{R^2 - 2R\rho\cos(\theta - t) + \rho^2}\log|F(h(Re^{it}))|\,\mathrm{d}t \qquad (17)$$

is valid for every $|\zeta| < R$. By [Rud87, p. 236] we have

$$\frac{R - \rho}{R + \rho} \leq \frac{R^2 - \rho^2}{R^2 - 2R\rho\cos(\theta - \varphi) + \rho^2} \leq \frac{R + \rho}{R - \rho} \qquad (18)$$

for $0 \leq \rho < R$. Combining (15) and (18) yields

$$\frac{R^2 - \rho^2}{R^2 - 2R\rho\cos(\theta - t) + \rho^2}\log|F(h(\zeta))| \leq \frac{R + \rho}{R - \rho}g(\theta) =: G(\theta) \qquad (19)$$

where $G \in L^1[-\pi, \pi]$. For $0 < R < 1$ let

$$f_R(\varphi) := \frac{R^2 - \rho^2}{R^2 - 2R\rho\cos(\theta - \varphi) + \rho^2}\log|F(h(Re^{i\varphi}))|$$

and for $\varphi \notin \{0, \pi\}$

$$f(\varphi) := \frac{1 - \rho^2}{1 - 2\rho\cos(\theta - \varphi) + \rho^2}\log|F(h(e^{i\varphi}))|$$

Since $\log|F(h(\zeta))|$ is upper semicontinuous on $\overline{D} \setminus \{\pm 1\}$ by lemma **??** we get

$$\limsup_{R \nearrow 1} f_R(\varphi) = \limsup_{R \nearrow 1}\left[\frac{R^2 - \rho^2}{R^2 - 2R\rho\cos(\theta - \varphi) + \rho^2}\log|F(h(Re^{i\varphi}))|\right]$$

$$= \lim_{R \nearrow 1}\frac{R^2 - \rho^2}{R^2 - 2R\rho\cos(\theta - \varphi) + \rho^2}\limsup_{R \nearrow 1}\log|F(h(Re^{i\varphi}))|$$

$$= \frac{1 - \rho^2}{1 - 2\rho\cos(\theta - \varphi) + \rho^2}\log|F(h(e^{i\varphi}))| = f(\varphi)$$

using [Bou95, p. 363] and proposition **??**. The functions $G - f_R$ being non-negative, an application of Fatou's lemma yields

$$\int_{-\pi}^{\pi}\liminf_{R \nearrow 1}\left[G(\varphi) - f_R(\varphi)\right]\mathrm{d}\varphi \leq \liminf_{R \nearrow 1}\int_{-\pi}^{\pi}\left[G(\varphi) - f_R(\varphi)\right]\mathrm{d}\varphi$$

By [Bou95, p. 354], we get

$$\limsup_{R \nearrow 1}\int_{-\pi}^{\pi}\left[f_R(\varphi) - G(\varphi)\right]\mathrm{d}\varphi \leq \int_{-\pi}^{\pi}\limsup_{R \nearrow 1}\left[f_R(\varphi) - G(\varphi)\right]\mathrm{d}\varphi$$

and thus

$$\limsup_{R\nearrow 1} \int_{-\pi}^{\pi} f_R(\varphi)\,\mathrm{d}\varphi - \int_{-\pi}^{\pi} G(\varphi)\,\mathrm{d}\varphi = \limsup_{R\nearrow 1} \int_{-\pi}^{\pi} f_R(\varphi)\,\mathrm{d}\varphi - \lim_{R\nearrow 1}\int_{-\pi}^{\pi} G(\varphi)\,\mathrm{d}\varphi$$

$$= \limsup_{R\nearrow 1}\int_{-\pi}^{\pi}[f_R(\varphi) - G(\varphi)]\,\mathrm{d}\varphi$$

$$\leq \int_{-\pi}^{\pi}\limsup_{R\nearrow 1}[f_R(\varphi) - G(\varphi)]\,\mathrm{d}\varphi$$

$$\leq \int_{-\pi}^{\pi}\limsup_{R\nearrow 1} f_R(\varphi)\,\mathrm{d}\varphi - \int_{-\pi}^{\pi}\lim_{R\nearrow 1} G(\varphi)\,\mathrm{d}\varphi$$

$$= \int_{-\pi}^{\pi}\limsup_{R\nearrow 1} f_R(\varphi)\,\mathrm{d}\varphi - \int_{-\pi}^{\pi} G(\varphi)\,\mathrm{d}\varphi$$

by [Bou95, p. 358]. Hence

$$\limsup_{R\nearrow 1}\int_{-\pi}^{\pi} f_R(\varphi)\,\mathrm{d}\varphi \leq \int_{-\pi}^{\pi}\limsup_{R\nearrow 1} f_R(\varphi)\,\mathrm{d}\varphi$$

and so

$$\log|F(h(\zeta))| \leq \frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{1-\rho^2}{1-2\rho\cos(\theta-\varphi)+\rho^2}\log|F(h(e^{i\varphi}))|\,\mathrm{d}\varphi \qquad (20)$$

The lemma now follows from (20) by a change of variables. By stipulating $x := h(\zeta)$ we obtain

$$\zeta = h^{-1}(x) = \frac{e^{\pi ix} - i}{e^{\pi ix} + i} = \frac{\cos(\pi x) + i\sin(\pi x) - i}{\cos(\pi x) + i\sin(\pi x) + i}$$

$$= \frac{\cos(\pi x) + i\sin(\pi x) - i}{\cos(\pi x) + i\sin(\pi x) + i}\frac{\cos(\pi x) - i\sin(\pi x) - i}{\cos(\pi x) - i\sin(\pi x) - i}$$

$$= -i\frac{\cos(\pi x)}{1+\sin(\pi x)} = \left(\frac{\cos(\pi x)}{1+\sin(\pi x)}\right)e^{-i\pi/2} \qquad (21)$$

by

$$(\cos(\pi x) + i\sin(\pi x) - i)\,(\cos(\pi x) - i\sin(\pi x) - i)$$

$$= \cos^2(\pi x) - i\sin(\pi x)\cos(\pi x) - i\cos(\pi x) + i\sin(\pi x)\cos(\pi x)$$

$$+ \sin^2(\pi x) + \sin(\pi x) - i\cos(\pi x) - \sin(\pi x) - 1 = -2i\cos(\pi x)$$

and

$$(\cos(\pi x) + i\sin(\pi x) + i)\,(\cos(\pi x) - i\sin(\pi x) - i)$$

$$= \cos^2(\pi x) - i\sin(\pi x)\cos(\pi x) - i\cos(\pi x) + i\sin(\pi x)\cos(\pi x)$$

$$+ \sin^2(\pi x) + \sin(\pi x) + i\cos(\pi x) + \sin(\pi x) + 1 = 2 + 2\sin(\pi x)$$

From equality (21) we deduce $\rho = \frac{\cos(\pi x)}{1+\sin(\pi x)}$, $\theta = -\frac{\pi}{2}$ if $0 < x \leq \frac{1}{2}$ and $\rho = -\frac{\cos(\pi x)}{1+\sin(\pi x)}$, $\theta = \frac{\pi}{2}$ if $\frac{1}{2} \leq x < 1$. Let $0 < x \leq \frac{1}{2}$. Then we have

$$\frac{1-\rho^2}{1-2\rho\cos(\theta-\varphi)+\rho^2}$$

$$= \frac{1 + 2\sin(\pi x) + \sin^2(\pi x) - \cos^2(\pi x)}{1 + 2\sin(\pi x) + \sin^2(\pi x) + 2\cos(\pi x)\sin(\varphi)(1+\sin(\pi x)) + \cos^2(\pi x)}$$

$$= \frac{\sin(\pi x) + \sin^2(\pi x)}{1 + \sin(\pi x) + \cos(\pi x)\sin(\varphi)(1+\sin(\pi x))} = \frac{\sin(\pi x)}{1 + \cos(\pi x)\sin(\varphi)}$$

and also for $\frac{1}{2} \le x < 1$. Let Φ and Ψ be defined as in lemma (**??**). We have

$$e^{i\Phi(t)} = h^{-1}(it) = \frac{e^{-\pi t} - i}{e^{-\pi t} + i} \frac{e^{-\pi t} - i}{e^{-\pi t} - i} = \frac{e^{-2\pi t} - 2ie^{-\pi t} - 1}{e^{-2\pi t} + 1} = \frac{e^{-2\pi t} - 1}{e^{-2\pi t} + 1} - \frac{2ie^{-\pi t}}{e^{-2\pi t} + 1}$$

$$= \frac{e^{-2\pi t} - 1}{e^{-2\pi t} + 1} - \frac{2i}{e^{-\pi t} + e^{\pi t}} = \frac{1 - e^{2\pi t}}{1 + e^{2\pi t}} - \frac{2i}{e^{-\pi t} + e^{\pi t}} = -\tanh(\pi t) - i\operatorname{sech}(\pi t)$$

and thus

$$\sin(\Phi(t))\cosh(\pi t) = \sin(-i\log(-\tanh(\pi t) - i\operatorname{sech}(\pi t)))\cosh(\pi t)$$

$$= \frac{1}{2i}\left[-\tanh(\pi t) - i\operatorname{sech}(\pi t) + \frac{1}{\tanh(\pi t) + i\operatorname{sech}(\pi t)}\right]\cosh(\pi t)$$

$$= \frac{1}{2i}\left[\frac{\cosh(\pi t) - \tanh(\pi t)\sinh(\pi t) - 2i\tanh(\pi t) + \operatorname{sech}(\pi t)}{\tanh(\pi t) + i\operatorname{sech}(\pi t)}\right]$$

$$= \frac{1}{2i}\left[\frac{\cosh^2(\pi t) - \sinh^2(\pi t) - 2i\sinh(\pi t) + 1}{\sinh(\pi t) + i}\right]$$

$$= \frac{1 - i\sinh(\pi t)}{i\sinh(\pi t) - 1} = -1$$

Therefore the transformation formula yields

$$\frac{1}{2\pi}\int_{-\pi}^{0}\frac{\sin(\pi x)}{1 + \cos(\pi x)\sin(\varphi)}\log|F(h(e^{i\varphi}))|\,d\varphi = \frac{1}{2}\int_{-\infty}^{\infty}\frac{\sin(\pi x)}{\cosh(\pi t) - \cos(\pi x)}\log|F(it)|\,dt$$

and in a similar manner

$$\frac{1}{2\pi}\int_{0}^{\pi}\frac{\sin(\pi x)}{1 + \cos(\pi x)\sin(\varphi)}\log|F(h(e^{i\varphi}))|\,d\varphi = \frac{1}{2}\int_{-\infty}^{\infty}\frac{\sin(\pi x)}{\cosh(\pi t) + \cos(\pi x)}\log|F(1 + it)|\,dt$$

holds since

$$\sin(\Psi(t))\cosh(\pi t) = \sin(-i\log(-\tanh(\pi t) + i\operatorname{sech}(\pi t)))\cosh(\pi t)$$

$$= \frac{1}{2i}\left[-\tanh(\pi t) + i\operatorname{sech}(\pi t) - \frac{1}{-\tanh(\pi t) + i\operatorname{sech}(\pi t)}\right]\cosh(\pi t)$$

$$= \frac{1}{2i}\left[\frac{-\cosh(\pi t) + \tanh(\pi t)\sinh(\pi t) - 2i\tanh(\pi t) - \operatorname{sech}(\pi t)}{-\tanh(\pi t) + i\operatorname{sech}(\pi t)}\right]$$

$$= \frac{1}{2i}\left[\frac{-\cosh^2(\pi t) + \sinh^2(\pi t) - 2i\sinh(\pi t) - 1}{i - \sinh(\pi t)}\right]$$

$$= \frac{1 + i\sinh(\pi t)}{1 + i\sinh(\pi t)} = 1$$

Thus the case $y = 0$ is prooven.

The case $y \ne 0$. follows easily from the previous one. Fix $y \ne 0$ and define $G(z) := F(z + iy)$ for $z \in \overline{S}$. Then G is a holomorphic function in S and continuous on $\overline{S}$ as a composition of continuous and holomorphic functions. Moreover, the hypothesis on F yields

$$\log|G(z)| = \log|F(z + iy)| \le Ae^{\tau_0|\operatorname{Im} z + y|} \le Ae^{\tau_0|\operatorname{Im} z|}e^{\tau_0|y|} \tag{22}$$

for all $z \in \overline{S}$. The previous case yields for G with A replaced by $Ae^{\tau_0|y|}$

$$|G(x)| \le \exp\left(\frac{\sin(\pi x)}{2}\int_{-\infty}^{\infty}\left[\frac{\log|G(it)|}{\cosh(\pi t) - \cos(\pi x)} + \frac{\log|G(1 + it)|}{\cosh(\pi t) + \cos(\pi x)}\right]dt\right) \tag{23}$$

Now, observing $G(x) = F(x + iy)$, $G(it) = F(it + iy)$ and $G(1 + it) = F(1 + it + iy)$ yields the desired result. $\qquad\square$

An almost immediate consequence of the Lemma of I. I. Hirschman 1.1 is the so called Hadamard's Three Lines Lemma.

Lemma 1.2 (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 $|F(z)| \leq B_0$ when $\operatorname{Re} z = 0$ and $|F(z)| \leq B_1$ when $\operatorname{Re} z = 1$, for some $0 < B_0, B_1 < \infty$. Then $|F(z)| \leq B_0^{1-x} B_1^x$ when $\operatorname{Re} z = x$, for any $0 < x < 1$.*

PROOF. Let $0 < x < 1$. Then

$$
\frac{\sin(\pi x)}{2} \int_{-\infty}^{\infty} \frac{1}{\cosh(\pi t) + \cos(\pi x)} \, dt = \frac{\sin(\pi x)}{2} \int_{-\infty}^{\infty} \frac{1}{\frac{1}{2}(e^{\pi t} + e^{-\pi t}) + \cos(\pi x)} \, dt
$$

$$
= \frac{\sin(\pi x)}{\pi} \int_0^{\infty} \frac{1}{s^2 + 2\cos(\pi x)s + 1} \, ds
$$

$$
= \frac{\sin(\pi x)}{\pi} \int_0^{\infty} \frac{1}{(s + \cos(\pi x))^2 + \sin^2(\pi x)} \, ds
$$

$$
= \frac{1}{\pi \sin(\pi x)} \int_0^{\infty} \frac{1}{\left(\frac{s + \cos(\pi x)}{\sin(\pi x)}\right)^2 + 1} \, ds
$$

$$
= \frac{1}{\pi} \int_{\cot(\pi x)}^{\infty} \frac{1}{u^2 + 1} \, du
$$

$$
= \frac{1}{\pi} \left[\frac{\pi}{2} - \arctan(\cot(\pi x))\right]
$$

$$
= x
$$

and in the same manner

$$
\frac{\sin(\pi x)}{2} \int_{-\infty}^{\infty} \frac{1}{\cosh(\pi t) - \cos(\pi x)} \, dt = 1 - x
$$

Assume that F is holomorphic in S, continuous and bounded on $\overline{S}$ with $|F(z)| \leq B_0$ when $\operatorname{Re} z = 0$ and $|F(z)| \leq B_1$ when $\operatorname{Re} z = 1$ for some $0 < B_0, B_1 < \infty$. If $|F(z)| \leq M$ for $0 < M < \infty$, F satisfies the hypothesis with $A := \log(M)$ and $\tau_0 = 0$. Therefore

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

$$
\leq \exp\left(\frac{\sin(\pi x)}{2} \int_{-\infty}^{\infty} \left[\frac{\log B_0}{\cosh(\pi t) - \cos(\pi x)} + \frac{\log B_1}{\cosh(\pi t) + \cos(\pi x)}\right] dt\right)
$$

$$
= \exp(x \log B_0 + (1 - x) \log B_1)
$$

$$
= B_0^x B_1^{1-x}
$$

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

1.2. The Stein-Weiss Interpolation Theorem for Analytic Families of Operators and the Riesz-Thorin Interpolation Theorem.

Definition 1.1 (Analytic family, admissible growth). *Let (X, μ), (Y, ν) be two σ-finite measure spaces and $(T_z)_{z \in \overline{S}}$, where T_z is defined Σ_X and taking values in the space of all measurable functions on Y such that*

$$
\int_Y |T_z(\chi_A)\chi_B| \, d\nu \tag{24}
$$

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*

$$z \mapsto \int_Y T_z(f)g \, \mathrm{d}\nu \tag{25}$$

is analytic on 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 $C(f, g)$ exists with*

$$\log \left| \int_Y T_z(f)g \, \mathrm{d}\nu \right| \leq C(f, g)e^{\tau_0 |\mathrm{Im}\, z|} \tag{26}$$

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

Theorem 1.1 (Stein-Weiss Interpolation Theorem of Analytic Families of Operators). *Let $(T_z)_{z \in \overline{S}}$ be an analytic family of admissible growth, $1 \leq p_0, p_1, q_0, q_1 \leq \infty$ and suppose that M_0, M_1 are positive functions on the real line such that for some $\tau_1 \in [0, \pi)$*

$$\sup_{-\infty < y < \infty} e^{-\tau_1 |y|} \log M_0(y) < \infty \qquad and \qquad \sup_{-\infty < y < \infty} e^{-\tau_1 |y|} \log M_1(y) < \infty. \tag{27}$$

Fix $0 < \theta < 1$ and define

$$\frac{1}{p} := \frac{1 - \theta}{p_0} + \frac{\theta}{p_1} \qquad and \qquad \frac{1}{q} := \frac{1 - \theta}{q_0} + \frac{\theta}{q_1}. \tag{28}$$

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

$$\|T_{iy}(f)\|_{L^{q_0}} \leq M_0(y) \|f\|_{L^{p_0}} \qquad and \qquad \|T_{1+iy}(f)\|_{L^{q_1}} \leq M_1(y) \|f\|_{L^{p_1}}. \tag{29}$$

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

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

where for $0 < x < 1$

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

PROOF. Fix $0 < \theta < 1$ and $f \in \Sigma_X$, $g \in \Sigma_Y$ with $\|f\|_{L^p} = \|g\|_{L^{q'}} = 1$. Define f_z, g_z as in (**??**) and for $z \in \overline{S}$

$$F(z) := \int_Y T_z(f_z)g_z \, \mathrm{d}\nu$$

Since the family $(T_z)_{z \in \overline{S}}$ is of admissible growth we have that there exist constants $c(\chi_{A_j}, \chi_{B_k})$ for any $j = 1, \ldots, n$ and $k = 1, \ldots, m$ such that

$$\log \left| \int_{B_k} T_z\left(\chi_{A_j}\right) \mathrm{d}\nu \right| \leq c\left(\chi_{A_j}, \chi_{B_k}\right) e^{\tau_0 |\mathrm{Im}\, z|}$$

For shortness we will denote these constants simply by $c(A_j, B_k)$ and get

$$\log |F(z)| = \log \left| \sum_{j=1}^{n} \sum_{k=1}^{m} a_j^{P(z)} b_j^{Q(z)} e^{i\alpha_j} e^{i\beta_k} \int_Y T_z(\chi_{A_j})(y) \chi_{B_k}(y) \, \mathrm{d}\nu(y) \right|$$

$$\leq \log \left[\sum_{j=1}^{n} \sum_{k=1}^{m} \max\{1, a_j^{p/p_0 + p/p_1}\} \max\{1, b_k^{q'/q_0' + q'/q_1'}\} \left| \int_{B_k} T_z(\chi_{A_j}) \, \mathrm{d}\nu \right| \right]$$

$$\leq \log \left[\sum_{j=1}^{n} \sum_{k=1}^{m} (1 + a_j)^{p/p_0 + p/p_1} (1 + b_k)^{q'/q_0' + q'/q_1'} e^{c(A_j, B_k) e^{\tau_0 |\mathrm{Im}\, z|}} \right]$$

$$\leq \log \left[\sum_{j=1}^{n} \sum_{k=1}^{m} e^{\log((1+a_j)^{p/p_0 + p/p_1} (1+b_k)^{q'/q_0' + q'/q_1'}) + c(A_j, B_k) e^{\tau_0 |\mathrm{Im}\, z|}} \right]$$

$$\leq \log \left(mn e^{\sum_{j=1}^{n} \sum_{k=1}^{m} \log((1+a_j)^{p/p_0 + p/p_1} (1+b_k)^{q'/q_0' + q'/q_1'}) + c(A_j, B_k) e^{\tau_0 |\mathrm{Im}\, z|}} \right)$$

$$= \log(mn) + \sum_{j=1}^{n} \sum_{k=1}^{m} \log \left((1 + a_j)^{p/p_0 + p/p_1} (1 + b_k)^{q'/q_0' + q'/q_1'} \right) + c(A_j, B_k) e^{\tau_0 |\mathrm{Im}\, z|}$$

since $\tau_0 \in [0, \pi)$ and thus $e^{\tau_0 |\mathrm{Im}\, z|} \geq 1$, F satisfies the hypotheses of the extension of Hadamard's three lines lemma **??** with

$$A = \log(mn) + \sum_{j=1}^{n} \sum_{k=1}^{m} \left(\frac{p}{p_0} + \frac{p}{p_1} \right) \log(1 + a_j) + \left(\frac{q'}{q_0'} + \frac{q'}{q_1'} \right) \log(1 + b_k) + c(A_j, B_k)$$

The same calculations as in the proof of the Riesz-Thorin interpolation theorem **??** yield for $y \in \mathbb{R}$

$$\|f_{iy}\|_{L^{p_0}} = \|f\|_{L^p}^{p/p_0} = 1 = \|g\|_{L^{q'}}^{q'/q_0'} = \|g_{iy}\|_{L^{q_0'}}$$

and

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

Further

$$\|F(iy)\| \leq \|T_{iy}(f_{iy})\|_{L^{q_0}} \|g_{iy}\|_{L^{q_0'}} \leq M_0(y) \|f_{iy}\|_{L^{p_0}} \|g_{iy}\|_{L^{q_0'}} = M_0(y)$$

and

$$\|F(1 + iy)\| \leq \|T_{1+iy}(f_{1+iy})\|_{L^{q_1}} \|g_{1+iy}\|_{L^{q_1'}} \leq M_1(y) \|f_{1+iy}\|_{L^{p_1}} \|g_{1+iy}\|_{L^{q_1'}} = M_1(y)$$

by Hölder's inequality and the hypotheses on the analytic family $(T_z)_{z \in \overline{S}}$. Therefore the extension of Hadamard's three lines lemma **??** yields

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

for every $0 < x < 1$. Furthermore observe that

$$F(\theta) = \int_Y T_\theta(f) g \, \mathrm{d}\nu$$

and thus by [Fol99, p. 189]

$$M_q(T_\theta(f)) = \sup\left\{\left|\int_Y T_\theta(f)g\,\mathrm{d}\nu\right| : g \in \Sigma_Y, \|g\|_{L^{q'}}\right\}$$
$$= \sup\{|F(\theta)| : g \in \Sigma_Y, \|g\|_{L^{q'}}\}$$
$$\leq M(\theta)$$

Since $M(\theta)$ is an absolutely convergent integral (this is immediate by the growth conditions (27)) for any $0 < \theta < 1$, $M_q(T_\theta(f)) < \infty$ and thus $M_q(T_\theta(f)) = \|T_\theta(f)\|_{L^q}$. The general statement follows by replacing f with $f/\|f\|_{L^p}$ when $\|f\|_{L^p} \neq 0$. The theorem is trivially true when $\|f\|_{L^p} = 0$. $\qquad\square$

Theorem 1.2 (Riesz-Thorin interpolation theorem). *Suppose that (X, μ), (Y, ν) are measure spaces and $1 \leq p_0, p_1, q_0, q_1 \leq \infty$. 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 for some $0 < M_0, M_1 < \infty$ the estimates*

$$\|T(f)\|_{L^{q_0}} \leq M_0 \|f\|_{L^{p_0}} \quad and \quad \|T(f)\|_{L^{q_1}} \leq M_1 \|f\|_{L^{p_1}} \tag{30}$$

hold for all $f \in \Sigma_X$. Then for all $0 \leq \theta \leq 1$ we have

$$\|T(f)\|_{L^q} \leq M_0^{1-\theta} M_1^\theta \|f\|_{L^p} \tag{31}$$

for all $f \in \Sigma_X$, where

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

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