University of Cambridge Mathematical Tripos Part II

Linear Analysis

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Course schedule

Normed and Banach spaces. Linear mappings, continuity, boundedness, and norms. Finite-dimensional normed spaces. [4]

The Baire category theorem. The principle of uniform boundedness, the closed graph theorem and the inversion theorem; other applications. [5]

The normality of compact Hausdorff spaces. Urysohn's lemma and Tiezte's extension theorem. Spaces of continuous functions. The Stone–Weierstrass theorem and applications. Equicontinuity: the Ascoli–Arzelá theorem. [5]

Inner product spaces and Hilbert spaces; examples and elementary properties. Orthonormal systems, and the orthogonalization process. Bessel's inequality, the Parseval equation, and the Riesz–Fischer theorem. Duality; the self duality of Hilbert space. [5]

Bounded linear operations, invariant subspaces, eigenvectors; the spectrum and resolvent set. Compact operators on Hilbert space; discreteness of spectrum. Spectral theorem for compact Hermitian operators. [5]

Recommended books

B. Bollobas *Linear Analysis.* Cambridge University Press 1999.
G.J.O. Jameson *Topology and Normed Spaces.* Chapman and Hall 1974.
G. Allan *Introduction to Banach Spaces and Algebras.* Oxford University Press 2010.
W. Rudin *Real and Complex Analysis.* McGraw–Hill International Edition 1987.

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1 Normed spaces and bounded linear maps

1.1 Definitions and examples

Let X be a vector space over $\mathbb{R}$ or $\mathbb{C}$. For ease of notation and discussion, we will sometimes just take our scalars to be in $\mathbb{R}$, although the statement may be easily generalised to $\mathbb{C}$-vector spaces.

Definition Norm
A norm *on X is a function $||\cdot||\colon X \to \mathbb{R}$ such that*
(i) $||x|| \geq 0$ *for all* $x \in X$*, with* $||x|| = 0$ *iff* $x = 0$
(ii) $||\lambda x|| = |\lambda|||x||$ *for all* $x \in X$ *and any scalar* λ
(iii) $||x+y|| \leq ||x|| + ||y||$ *for all* $x, y \in X$

Definition Normed space
A normed space *is a pair $(X, ||\cdot||)$ where X is a vector space and $||\cdot||$ is a norm on X.*

Example *Some finite-dimensional normed spaces*
(1) $\ell_2^n = (\mathbb{R}^n, ||\cdot||_2)$ or $(\mathbb{C}^n, ||\cdot||_2)$, where the norm is given by

$$||x||_2 = \left(\sum_{i=1}^n |x_i|^2\right)^{1/2}, \qquad x = (x_1, \cdots, x_n) \in \mathbb{R}^n$$

This is called the ℓ_2-norm or euclidean norm.

(i),(ii) are easy to check, whereas (ii) follows from Cauchy-Schwarz.

(2) $\ell_1^n = (\mathbb{R}^n, ||\cdot||_1)$ where $||x||_1 = \sum_{i=1}^n |x_i|$ (called the ℓ_1- norm)

(3) $\ell_\infty^n = (\mathbb{R}^n, ||\cdot||_\infty)$ where $||x||_\infty = \max_{1\leq i\leq n} |x_i|$ (called the ℓ_∞-norm or the sup-norm)

Given a normed space X, its norm $||\cdot||$ induces a metric on X:

$$d(x,y) = ||x-y||$$

Indeed, d is a metric:
- $d(x,y) \geq 0$ for all $x, y \in X$, with $d(x,y) = 0 \iff x - y = 0 \iff x = y$
- $d(x,y) = ||x-y|| = ||y-x|| = d(y,x)$
- $d(x,z) = ||x-z|| \leq ||x-y|| + ||y-z|| = d(x,y) + d(y,z)$

This metric, in turn, induces a topology on X, called the *norm topology.* This allows us talk about open/closed sets, convergence, and continuity, as we illustrate in the following examples.

Example
The algebraic operations are continuous:
- if $x_n \to x$ and $y_n \to y$ in X, then $x_n + y_n \to x + y$
- if $x_n \to x$ in X and $\lambda_n \to \lambda$ in $\mathbb{R}$, then $\lambda_n x_n \to \lambda x$

Example
The norm $||\cdot||\colon X \to \mathbb{R}$ is continuous: by the triangle inequality, we have

$$|||x|| - ||y||| \leq ||x-y||$$

so $||\cdot||$ is, in fact, Lipschitz.

Definition Banach space

A Banach space *is a complete normed space, i.e., a normed space that is complete in its norm topology.*

Example

ℓ_2^n, ℓ_1^n, ℓ_∞^n are complete: for any of these spaces,

- $x^{(k)} \to x \iff x_i^{(k)} \to x_i$ for all $1 \le i \le n$
- $(x^{(k)})_{k\in\mathbb{N}}$ is Cauchy $\iff (x_i^{(k)})_{k\in\mathbb{N}}$ is Cauchy for all $1 \le i \le n$

In a normed space, a useful object is the *unit ball*

$$B_X := \{x \in X \colon ||x|| \le 1\}$$

Remarks

- B_X defines a norm on X:
$$||x|| = \inf\{t \ge 0 \colon x \in tB_X\}$$
- B_X is symmetric ($x \in B_X \implies -x \in B_X$), convex, and closed
- If $B \subset \mathbb{R}^n$ is a closed, convex, symmetric, bounded neighbourhood of 0, then B is the unit ball of $(\mathbb{R}^n, ||\cdot||)$ for some norm $||\cdot||$
- 'Geometry of Banach spaces'

Previously, we gave $\ell_2, \ell_1, \ell_\infty$ as examples of finite-dimensional normed spaces. More generally, we have the following family of examples

Example

(4) $\ell_p^n = (\mathbb{R}^n, ||\cdot||_p)$ for $1 \le p < \infty$, where $||x|| = (\sum_{i=1}^n |x_i|^p)^{1/p}$ (called the ℓ_p-norm)

Again, (i) and (ii) are easy to check, whereas (iii) is not obvious.[1]

Now, let S denote the set of all scalar sequences. This is a vector spaces under the coordinate operations $(x_n) + (y_n) = (x_n + y_n)$ and $\lambda(x_n) = (\lambda x_n)$.

Example *Sequence spaces*

(5) $\ell_1 = \left\{(x_n) \in S \colon \sum_{n=1}^{\infty} |x_n| < \infty\right\}$, $\quad ||(x_n)||_1 = \sum_{n=1}^{\infty} |x_n| \quad$ (ℓ_1-norm)

(i) and (ii): easy to check.

(iii): Given $(x_n), (y_n) \in \ell_1$, we have $|x_n + y_n| \le |x_n| + |y_n|$ for all $n \in \mathbb{N}$. Summing over all $n \in \mathbb{N}$, we deduce that $(x_n) + (y_n) \in \ell_1$ and $||(x_n) + (y_n)||_1 \le ||(x_n)||_1 + ||(y_n)||_1$. Hence, ℓ_1 is a subspace of S and $||\cdot||_1$ is a norm on ℓ_1.

(6) $\ell_2 = \left\{(x_n) \in S \colon \sum_{n=1}^{\infty} |x_n|^2 < \infty\right\}$, $\quad ||(x_n)||_1 = \left(\sum_{n=1}^{\infty} |x_n|^2\right)^{1/2} \quad$ (ℓ_1-norm)

(i) and (ii): easy to check.

(iii): Given $(x_n), (y_n) \in \ell_2$, the triangle inequality in ℓ_2^N gives us

$$\left(\sum_{k=1}^{N} |x_k + y_k|^2\right)^{1/2} \le \left(\sum_{k=1}^{N} |x_k|^2\right)^{1/2} + \left(\sum_{k=1}^{N} |y_k|^2\right)^{1/2}.$$

Taking $N \to \infty$, we get $(x_n) + (y_n) \in \ell_2$ and $||(x_n) + (y_n)||_2 \le ||(x_n)||_2 + ||(y_n)||_2$

[1] We will return to this later in the next subsection.

More generally, for $1 \le p < \infty$, the set
$$\ell_p = \left\{ (x_n) \in S \colon \sum_{n=1}^{\infty} |x_n|^p < \infty \right\}$$
is a subspace of S, and
$$||(x_n)||_p = \left(\sum_{n=1}^{\infty} |x_n|^p \right)^{1/p} \qquad (\ell_p\text{-norm})$$
is a norm on ℓ_p. [Verifying (iii) follows from the triangle inequality on ℓ_p^n, which we will see later.]

Example *More sequence spaces*

(7) $\ell_\infty = \{(x_n) \in S \colon \exists\, M \ge 0\ \forall\, n \in \mathbb{N}\ |x_n| \le M\}$, $\quad ||(x_n)||_\infty = \sup_{n\in\mathbb{N}} |x_n| \quad$ (ℓ_∞-norm)

(i) and (ii): easy to check.
(iii): Given $x = (x_n), y = (y_n) \in \ell_\infty$,
$$|x_n + y_n| \le |x_n| + |y_n| \le ||x||_\infty + ||y||_\infty \quad \forall\, n \in \mathbb{N}$$
so $x + y \in \ell_\infty$ and $||x + y||_\infty \le ||x||_\infty + ||y||_\infty$.

(8) $c_0 = \{(x_n) \in S \colon x_n \to 0 \text{ as } n \to \infty\}$
$c = \{(x_n) \in S \colon \lim_{n\to\infty} x_n \text{ exists}\}$

Both c_0 and c are subspaces of ℓ_∞ and are hence normed spaces in the ℓ_∞-norm.

1.2 Inequalities of Minkowski and Hölder

Recall that a function $f \colon (0, \infty) \to \mathbb{R}$ is *convex* if
$$f((1-t)x + ty) \le (1-t)f(x) + tf(y) \qquad \forall\, x, y \in (0, \infty) \forall\, t \in [0, 1]$$
and concave if the above holds with $\le$ replaced by $\ge$.

Lemma 1.1
Let $1 \le p < \infty$. Then the map
$$\begin{aligned} (0, \infty) &\to \mathbb{R} \\ x &\mapsto x^p \end{aligned}$$
is convex.

Proof. Fix $y > 0, t \in [0, 1]$, and define
$$g(x) = [(1-t)x + ty]^p - [(1-t)x^p + ty^p], \qquad x > 0$$
Differentiating, we get
$$g'(x) = p(1-t)[(1-t)x + ty]^{p-1} - p(1-t)x^{p-1}$$
Observe that $0 < x < y \implies g'(x) \ge 0$ and that $x > y \implies g'(x) \le 0$. By the MVT, we deduce that $g(x) \le g(y) = 0$ for all $x \in (0, \infty)$. ∎

Theorem 1.2 Minkowski's inequality
Let $1 \le p < \infty$, $n \in \mathbb{N}$. For $x, y \in \mathbb{R}^n$,
$$||x + y||_p \le ||x||_p + ||y||_p$$

Remark. This shows that ℓ_p^n and ℓ_p are normed spaces.

Exercise. Show that $\ell_p, 1 \leq p \leq \infty$, is complete.[2]

Proof of Theorem 1.2. Let $B = \{x \in \mathbb{R}^n \colon ||x||_p \leq 1\}$. We first show that B is convex. Let $x, y \in B$ and $t \in [0,1]$. For $1 \leq k \leq n$,

$$|(1-t)x_k + ty_k|^p \leq ((1-t)|x_k| + t|y_k|)^p \leq (1-t)|x_k|^p + t|y_k|^p$$

by Lemma 1.1 for $x_k \neq 0, y_k \neq 0$ (the inequality holds trivially if $x_k = 0$ or $y_k = 0$). Summing over k, we then get

$$||(1-t)x + ty||_p^p \leq (1-t)||x||_p^p + t||y||_p^p \leq 1,$$

so $(1-t)x + ty \in B$.

We then complete the proof as follows: Let $x, y \in \mathbb{R}^n$. We need $||x+y||_p \leq ||x||_p + ||y||_p$. WLOG $x, y, x+y$ are nonzero. By convexity of B,

$$\frac{x+y}{||x||_p + ||y||_p} = \frac{||x||_p}{||x||_p + ||y||_p} \cdot \underbrace{\frac{x}{||x||_p}}_{\in B} + \frac{||y||_p}{||x||_p + ||y||_p} \cdot \underbrace{\frac{y}{||y||_p}}_{\in B} \in B$$

Thus,

$$\left|\left|\frac{x+y}{||x||_p + ||y||_p}\right|\right| \leq 1 \Longrightarrow ||x+y||_p \leq ||x||_p + ||y||_p$$

as required. ■

Let $x = (x_n) \in \ell_1$ and $y = (y_n) \in \ell_\infty$. We then write $x \cdot y = (x_n y_n)$. Note that, for all $n \in \mathbb{N}$, $|x_n y_n| = |x_n||y_n| \leq |x_n| ||y||_\infty$. Thus, $x \cdot y \in \ell_1$ and $||x \cdot y||_1 \leq ||x||_1 ||y||_\infty$.

Definition Conjugate index
Let $p \in (1, \infty)$. The conjugate index of p is the unique $q \in (1, \infty)$ such that $\frac{1}{p} + \frac{1}{q} = 1$.

Lemma 1.3
Let $1 < p, q < \infty$ such that $\frac{1}{p} + \frac{1}{q} = 1$. Then, for $a, b \geq 0$, we have

$$ab \leq \frac{a^p}{p} + \frac{b^q}{q}$$

Proof. The inequality holds trivially if $a = 0$ or $b = 0$, so it remains to consider the case $a, b > 0$. A proof similar to that of Lemma 1.1 shows that $\log \colon (0, \infty) \to \mathbb{R}$ is concave. Hence,

$$\log\left(\frac{a^p}{p} + \frac{b^q}{q}\right) \geq \frac{1}{p}\log(a^p) + \frac{1}{q}\log(b^q) = \log(ab)$$

We then apply exp to get the required result. ■

Theorem 1.4 Hölder's inequality
Let $1 < p, q < \infty$ such that $\frac{1}{p} + \frac{1}{q} = 1$. If $x \in \ell_p$ and $y \in \ell_q$, then $x \cdot y \in \ell_1$ and $||x \cdot y||_1 \leq ||x||_p ||y||_q$.

Remark. As discussed above, $p = 1, q = \infty$ also works. Moreover, setting $p = q = 2$, we recover Cauchy-Schwarz.

Exercise. Deduce Minkowski's inequality from Hölder's inequality.

[2] A slick proof of this will be provided later.

Proof of Theorem 1.4. WLOG, $x \neq 0$ and $y \neq 0$. By homogeneity, we may also take $||x||_p = ||y||_q = 1$ WLOG. Now, by Lemma 1.3, we have $|x_n y_n| \leq |x_n|^p/p + |y_n|^q/q$ for all $n \in \mathbb{N}$. Summing over n, we have

$$\sum_{n=1}^{\infty} |x_n y_n| \leq \frac{||x||_p^p}{p} + \frac{||y||_q^q}{q} = \frac{1}{p} + \frac{1}{q} = 1 = ||x||_p ||y||_q,$$

as required. ■

1.3 More examples: function spaces

Example

(9) $C[0,1] = \{f\colon [0,1] \to \mathbb{R} \mid f \text{ cts}\}$, $\quad ||f||_\infty = \sup_{[0,1]} |f|$ (sup norm or uniform norm)

By the uniform limit theorem, this is a Banach space.

(10) More generally, given a compact, Hausdorff topological space K,

$$C(K) = \{f\colon K \to \mathbb{R} \mid f \text{ cts}\}$$

is a Banach space in the sup norm $||f||_\infty = \sup_K |f|$.

(11) $(C[0,1], ||\cdot||_1)$, $\quad ||\cdot||_1 = \int_0^1 |f(t)|\,dt$ (L_1-norm)

This is an *incomplete* normed space — see Example Sheet 1.

More generally, $C[0,1]$ is incomplete in the L_p-norm, $1 \leq p < \infty$, given by

$$||f||_p = \left(\int_0^1 |f(t)|^p\,dt\right)^{1/p}$$

Aside: In II Probability and Measure, you will encounter the completion of $(C[0,1], ||\cdot||_p)$, which are the Lebesgue spaces $L_p[0,1]$.

Example

(12) $C^1[0,1] = \{f \in C[0,1] \mid f \text{ continuously differentiable}\}$ is a subspace of $C[0,1]$, so it is a normed space in $||\cdot||_\infty$ but incomplete, i.e. not closed in $C[0,1]$. However, it is complete in the norm $||f|| = ||f||_\infty + ||f'||_\infty$ — see Example Sheet 1.

(13) Let $\triangle = \{z \in \mathbb{C} \mid |z| \leq 1\}$. The set

$$A(\triangle) = \{f \in C(\triangle) \mid f \text{ analytic on } \operatorname{int}\triangle\}$$

is a subspace of $C(\triangle)$. In fact, it is closed in $C(\triangle)$ and hence a Banach space in $||\cdot||_\infty$.

1.4 More on the normed topology

Let X be a normed space and $A \subset C$. Recall that the *closure* of A in X is

$$\overline{A} = \{x \in X \mid \exists\,(a_n) \text{ in } X \text{ s.t. } a_n \to x \text{ as } n \to \infty\}.$$

We then say that A is *dense* in X if $\overline{A} = X$. Moreover, A is *separable* if it has a countable dense subset.

If $Y \subset X$ is a subspace, then so is $\overline{Y}$: if $x, y \in \overline{Y}$, then there exists (x_n), (y_n) in Y such that $x_n \to x$ and $y_n \to y$. So $\lambda x_n + \mu y_n \to \lambda x + \mu y \in \overline{Y}$. Similarly, if $A \subset X$ is convex, then so is $\overline{A}$.

For a subset $A \subset X$, the *closed linear span* of A, denoted by $\overline{\operatorname{span}}\,A$, is the closure of $\operatorname{span} A$.

Remarks

- If A is countable, then $\overline{\operatorname{span}}\, A$ is separable.
- The set of all rational linear combinations of elements of A is countable and dense in $\overline{\operatorname{span}}\, A$.

Example

- $\overline{\mathbb{Q}} = \mathbb{R}$, so $\mathbb{R}$ is separable.
- $\ell_p, 1 \leq p < \infty$, is separable.
  Let $e_n = (0, \cdots, 0, \underset{n}{1}, 0, \cdots)$, $n \in \mathbb{N}$ (unit vector basis)
  Let $c_{00} = \operatorname{span}\{e_n : n \in \mathbb{N}\} = \{(x_n) \in S : \exists\, N \in \mathbb{N}\ \forall n > N x_n = 0\}$
  We then show that $\ell_p = \overline{\operatorname{span}}\{e_n : n \in \mathbb{N}\}$: if $x = (x_n) \in \ell_p$, then
  $$\left|\left| x - \sum_{i=1}^{N} x_i e_i \right|\right|_p = \left(\sum_{i>n} |x_i|^p \right)^{1/p} \to 0 \text{ as } N \to \infty$$
- Similarly, in ℓ_∞, we have $\overline{\operatorname{span}}\{e_n : n \in \mathbb{N}\} = c_0$. Moreover, c is separable, whereas ℓ_∞ is not.

Exercise. Prove the claims in the last example above.

1.5 Bounded linear maps

Theorem 1.5

Let X, Y be normed spaces and $T : X \to Y$ be a linear map. The following are equivalent:

(i) *T is continuous at* 0

(ii) *T is continuous*

(iii) *T is Lipschitz*

(iv) *T is bounded, i.e., $\exists\, C \geq 0\ \forall x \in X\ ||Tx|| \leq C||x||$.*

Proof. (iv) $\implies$ (iii): Observe that

$$d(Tx, Ty) = ||Tx - Ty|| = ||T(x-y)|| \leq C||x - y|| = Cd(x, y)$$

iii) $\implies$ (ii): Given $\varepsilon > 0$ take $\delta = \varepsilon/(C+1)$.
(ii) $\implies$ (i): Trivial.
(i) $\implies$ (iv): $\exists\, \delta > 0\ \forall x \in X\ d(x, 0) = ||x|| \leq \delta \implies d(Tx, T0) = ||Tx|| \leq 1$. For $x \neq 0$, $||\delta x/||x|||| = \delta$, so $||T(\delta x/||x||)|| \leq 1$. Hence, $||Tx|| \leq \delta^{-1}||x||$. ∎

For normed spaces X, Y, let $\mathcal{B}(X, Y) = \{T : X \to Y \mid T \text{ linear and bounded}\}$. For $T \in \mathcal{B}(X, Y)$, its *operator norm* is

$$||T|| = \sup\{||Tx|| : x \in B_X\}.$$

Remark. Since $T \in \mathcal{B}(X, Y)$, we have $C \geq 0$ such that $||Tx|| \leq C||x||$ for all $x \in X$. So if $||x|| \leq 1$, then $||Tx|| \leq C$. Thus, by definition, $||T|| \leq C$. Conversely, for all $x \in B_X$, we have $||Tx|| \leq ||T||$, so by homogeneity, $||Tx|| \leq ||T||||x||$. Hence, $||T||$ is the least C such that (iv) in Theorem 1.5 above holds.

The operator norm is a norm on $\mathcal{B}(X, Y)$: given $S, T \in \mathcal{B}(X, Y)$, we have, for all $x \in X$,

$$||(S+T)x|| = ||Sx + Tx|| \leq ||Sx|| + ||Tx|| \leq ||S||||x|| + ||T||||x|| \leq (||S|| + ||T||)||x||,$$

from which it follows that $S + T \in \mathcal{B}(X, Y)$ and $||S + T|| \leq ||S|| + ||T||$.

Notation. We write $\mathcal{B}(X)$ for $\mathcal{B}(X, X)$.

Proposition 1.6
Let X, Y, Z be normed spaces, $S \in \mathcal{B}(X,Y)$, $T \in \mathcal{B}(Y,Z)$. Then $TS \in \mathcal{B}(X,Z)$ and $||TS|| \leq ||T||||S||$.

Proof. For all $x \in X$, we have $||TSx|| \leq ||T||||Sx|| \leq ||T||||S||||x||$. ∎

Example

(1) $T\colon \ell_2^n \to \ell_2^n, (x_1, \cdots, x_n) \mapsto (x_1, \cdots, x_r, 0, \cdots, 0)$

$$||Tx||_2 = \left(\sum_{i=1}^{r} |x_i|^2\right)^{1/2} \leq ||x||_2 \implies ||T|| \leq 1$$

But $Te_1 = e_1$ so $||T|| = 1$.

More generally, if T is represented by a matrix A wrt the standard basis, then Cauchy-Schwarz gives us

$$||T|| \leq \left(\sum_{i,j=1}^{n} |a_{ij}|^2\right)^{1/2}$$

(2) Let $1 \leq p < \infty$, $R\colon \ell_p \to \ell_p, (x_1, x_2, x_3, \cdots) \mapsto (0, x_1, x_2, \cdots)$ (right shift)

For all $x \in \ell_p$, $||Rx||_p = ||x||_p$, so R is isometric and $||R|| = 1$. Note that R is injective but not surjective.

(3) Let $1 \leq p < \infty$, $L\colon \ell_p \to \ell_p, (x_1, x_2, x_3, \cdots) \mapsto (x_2, x_3, x_4, \cdots)$ (left shift)

For all $x \in \ell_p$, $||Lx||_p \leq ||x||_p$, so $L \in \mathcal{B}(\ell_p)$ with $||L|| \leq 1$. Since $Le_2 = e_1$ and $||e_1||_p = ||e_2||_p = 1$, we in fact have $||L|| = 1$. Note that L is surjective but not injective.

(4) $T\colon \ell_1 \to \ell_2, x \mapsto x$

- **Claim.** $\ell_1 \subset \ell_2$, and $\forall\, x \in \ell_2$ $||x||_2 \leq ||x||_1$

  Proof. WLOG assume $||x||_1 = 1$ by homogeneity. Since $\sum |x_i| = 1$, we have $|x_i| \leq 1$ for all i. Thus,

  $$|x_i|^2 \leq |x_i| \;\forall\, i \implies ||x||_2^2 \leq ||x||_1 = 1 \implies ||x||_2 = 1 = ||x||_1$$

  as claimed. ∎

Using the above claim, we have $T \in \mathcal{B}(\ell_1, \ell_2)$ and $||T|| = 1$.

(5) $T\colon \ell_2 \to \ell_1, (x_n) \mapsto (x_n/n)$

By Cauchy-Schwarz,

$$\sum \left|\frac{x_i}{n}\right| \leq \left(\sum x_i^2\right)^{1/2} \left(\sum \frac{1}{n^2}\right)^{1/2}$$

so $T \in \mathcal{B}(\ell_2, \ell_1)$ with $||T|| \leq \left(\sum \frac{1}{n^2}\right)^{1/2}$. In fact, we can replace $\leq$ with $=$.

(6) $D\colon (C^1[0,1], ||\cdot||) \to (C[0,1], ||\cdot||_\infty), f \mapsto f'$

Note that $||Df||_\infty = ||f'||_\infty \leq ||f||_\infty + ||f'||_\infty = ||f||$, so $||D|| \leq 1$. But taking $f(x) = \sin(n\pi x)$, we have

$$||Df||_\infty = n\pi, \qquad ||f|| = n\pi + 1,$$

so in fact $||D|| = 1$. Note also that, for $f \neq 0$, $||Df||_\infty < ||f||$, so $||D||$ is not attained.

(7) On a normed space X, the identity $x \mapsto x$ is denoted by Id, I, Id_X or I_X. This map is isometric, i.e., $||\mathrm{Id}(x)|| = ||x|| \; \forall\, x \in X$.

(8) For normed spaces X, Y, we let

$$X \oplus Y = \{(x, y) \colon x \in X, y \in Y\}$$

with norm $||(x, y)||_1 = ||x|| + ||y||$. The corresponding norm topology is the product topology.

Define $P \colon X \oplus Y \to X, (x, y) \mapsto x$ [projection onto X]. Note that $P \in \mathcal{B}(X \oplus Y, X)$ with $||P|| = 1$.

Let X, Y be normed spaces. We introduce some terminology for certain bounded linear maps $X \to Y$:

- An *isomorphism* $X \to Y$ is a linear homeomorphism $T \colon X \to Y$, i.e., T is a linear bijection such that T and T^{-1} are bounded. Equivalently, T is a linear bijection[3] such that

$$\exists\, a, b > 0 \; \forall\, x \in X \;\; a||x|| \leq ||Tx|| \leq b||x||$$

  If such T exists, we say that X and Y are *isomorphic*, and we write $X \sim Y$.
- An *isometric isomorphism* is a linear bijection $T \colon X \to Y$ such that

$$\forall\, x \in X \;\; ||Tx|| = ||x||$$

  If such T exists, we say that X and Y are *isometrically isomorphic*, and we write $X \cong Y$.

The Banach-Mazui distance is defined as

$$d(X, Y) = \begin{cases} \infty, & \text{if } X \not\sim Y \\ \inf\{||T||||T^{-1}|| \mid T \colon X \to Y \text{ is an isomorphism}\}, & \text{otherwise} \end{cases}$$

Note that $||T||||T^{-1}|| \geq ||TT^{-1}|| = 1$. If $X \cong Y$, then $d(X, Y) = 1$. Does the converse hold?

- An *isomorphic embedding* $X \to Y$ is a linear map $T \colon X \to Y$ such that $T \colon X \to TX = \operatorname{im} T$ is an isomorphism. If such T exists, we say that X *(isomorphically) embeds into* Y, and we write $X \hookrightarrow Y$.

Definition Equivalent norms
Let X be a normed space. Two norms $|| \cdot ||, || \cdot ||'$ are equivalent if

$$\begin{aligned} & \mathrm{Id} \colon (X, || \cdot ||) \to (X, || \cdot ||') \textit{ is an isomorphism} \\ \iff & || \cdot ||, || \cdot ||' \textit{ induce the same norm topology on } X \\ \iff & \exists\, a, b > 0 \; \forall\, x \in X a||x|| \leq ||x||' \leq b||x|| \\ \iff & \exists\, a, b > 0 \;\; aB'_X \subset B_X \subset bB'_X \end{aligned}$$

Remarks

- If $X \sim Y$, then X is complete iff Y is complete.
  If $||\cdot||, ||\cdot||'$ are equivalent norms on a vector space X, then $(X, ||\cdot||)$ is complete iff $(X, ||\cdot||')$ is complete.
- Let X and Y be normed spaces. On $X \oplus Y$, the norm $||(x, y)||_1 = ||x|| + ||y||$ is equivalent to $||(x, y)||_p = (||x||^p + ||y||^p)^{1/p}$ for all $1 \leq p < \infty$ and to $||(x, y)||_\infty = \max\{||x||, ||y||\}$.

[3] We can actually replace 'bijection' with 'surjection'.

- $(C[0,1], ||\cdot||_\infty)$ is complete whereas $(C[0,1], ||\cdot||_1)$ is incomplete. Thus, we can use the first remark above to deduce that $||\cdot||_\infty \not\sim ||\cdot||_1$ (but this can easily be proven directly as well). However, $||f||_1 = \int_0^1 |f(t)|\,dt \leq ||f||_\infty$, so
$$\mathrm{Id}\colon (C[0,1], ||\cdot||_\infty) \to (C[0,1], ||\cdot||_1)$$
is a continuous linear bijection but its inverse is not continuous.
- On c_{00}, $||\cdot||_1 \not\sim ||\cdot||_2$. To see why, consider $x = (\underbrace{1,\cdots,1}_{n}, 0, 0, \cdots)$. Note that $||x||_1 = n$ and $||x||_2 = \sqrt{n}$.

Finally, we discuss convergence and completeness. Let X, Y be normed spaces, In $\mathcal{B}(X,Y)$, convergence implies pointwise convergence, i.e., if $T_n \to T$ in $\mathcal{B}(X,Y)$, then, for all $x \in X$, $T_n x \to Tx$ in Y. To see why, note that, for fixed $x \in X$, we have $||T_n x - Tx|| \leq ||T_n - T||||x|| \to 0$. However, the converse is false in general, e.g., $T_n\colon \ell_1 \to \mathbb{R}, x \mapsto x_n$. We have $T_n \to 0$ pointwise, but $||T_n|| = 1$ for all $n \in \mathbb{N}$.

Theorem 1.7
Let X, Y be normed spaces. If Y is complete, then $\mathcal{B}(X,Y)$ is complete.

Proof. Let (T_n) be a Cauchy sequence in $\mathcal{B}(X,Y)$. Fix $x \in X$. Then
$$||T_m x - T_n x|| \leq ||T_m - T_n||||x|| \to 0 \text{ as } m, n \to \infty$$
So $(T_n x)$ is Cauchy in Y and thus convergent. Now, define $T\colon X \to Y$ by $x \mapsto \lim_{n\to\infty} T_n x$. Observe that

- T is linear
$$T(\lambda x + \mu y) = \lim_{n\to\infty} T_n(\lambda x + \mu y) = \lim_{n\to\infty} [\lambda T_n x + \mu T_n y] = \lambda Tx + \mu Ty$$
- T is bounded
(T_n) is Cauchy implies (T_n) is bounded, i.e., there exists $M \geq 0$ such that $||T_n|| \leq M$ for all $n \in \mathbb{N}$. Fix $x \in X$. Then, for all $n \in \mathbb{N}$, we have $||T_n x|| \leq ||T_n||||x|| \leq M||x||$. Letting $n \to \infty$, we obtain $||Tx|| \leq M||x||$.
- $T_n \to T$ in $\mathcal{B}(X,Y)$
Let $\varepsilon > 0$. Choose $N \in \mathbb{N}$ such that $||T_m - T_n|| \leq \varepsilon$ for all $m, n \geq N$. Fix $x \in X$. Note that, for all $m, n \geq N$, we have
$$||T_m x - T_n x|| \leq ||T_m - T_n||||x|| \leq \varepsilon||x||$$
Letting $n \to \infty$ with $m \geq N$ fixed yields $||T_m x - Tx|| \leq \varepsilon||x||$. Hence, $||T_m - T|| \leq \varepsilon$ for all $m \geq N$. ∎

2 Dual spaces

2.1 Basics

Let X be a normed space. A *functional* on X is a map $X \to \{\text{scalars}\}$. The *dual space* X^* of X is the space of all bounded linear functionals on X, i.e., $X^* = \mathcal{B}(X, \mathbb{R})$ or $\mathcal{B}(X, \mathbb{C})$ equipped with the operator norm. Since $\mathbb{R}$ is complete, Theorem 1.7 gives us

Theorem 2.1
For any normed space X, its dual X^* is a Banach space.

Notation. For $x \in X$ and $f \in X^*$, we let $\langle x, f \rangle = f(x)$.

Now, we know that $0 \in X^*$. Are there other elements?

Theorem 2.2 Hanh-Banach theorem
Let X be a normed space, $Y \subset X$ be a subspace and $g \in Y^*$. Then $f \in X^*$ such that $f|_Y = g$ and $||f|| = ||g||$.

Proof. See II Analysis of Functions. ■

Corollary 2.3
Let X be a normed space, $x_0 \in X \backslash \{0\}$. Then there exists $f \in S_{X^*} = \{f \in X^* \colon ||f|| = 1\}$ such that $f(x_0) = ||x_0||$.

Remarks

- For any $g \in B_{X^*}$, $|g(x_0)| \leq ||g|| ||x_0|| \leq ||x_0||$. Corollary 2.3 says that there exists $f \in B_{X^*}$ such that $f(x_0) = ||x_0||$, so

$$||x_0|| = \sup\{g(x_0) \colon g \in B_{X^*}\} = \max\{g(x_0) \colon g \in B_{X^*}\}.$$

  We call f a *norming functional* at x_0.
- Given $x \neq y$ in X, we can set $x_0 = x - y$ and Corollary 2.3 implies that there exists $f \in X^*$ such that $f(x) \neq f(y)$. Thus, X^* separates the points of X.

Proof of Corollary 2.3. Set $Y = \operatorname{span}\{x_0\}$ and define $g(\lambda x_0) = \lambda ||x_0||$. Then $g \in S_{Y^*}$ with $g(x_0) = ||x_0||$. Finally, apply Theorem 2.2. ■

2.2 Dual space of ℓ_p

Motivation: Recall that, for $1 \leq p < \infty$, we have $\ell_p = \overline{\operatorname{span}}\{e_n \colon n \in \mathbb{N}\} = \overline{c_{00}}$. Given $\varphi \in \ell_p^*$ and $x = (x_n) \in \ell_p$,

$$\varphi(x) = \varphi\left(\lim_{n\to\infty} \sum_{k=1}^{n} x_k e_k\right) = \sum_{k=1}^{\infty} x_k \varphi(e_k)$$

so φ corresponds to the sequence $y = (\varphi(e_n))_{n\in\mathbb{N}}$. We may then ask: is $\ell_p^* \cong \ell_q$ for some q?

Fix $1 < p < \infty$, and let q be the conjugate index of p. Fix $y = (y_n) \in \ell_q$. Define

$$\begin{aligned} \varphi_y \colon \ell_p &\to \mathbb{R} \\ x &\mapsto \sum_{n=1}^{\infty} x_n y_n \end{aligned}$$

By Holder's inequality (Theorem 1.4), this is well-defined and $|\varphi_y(x)| \leq ||x||_p||y||_q$. So φ_y is linear and bounded: $||\varepsilon_y|| \leq ||y||_q$. Thus, $\varphi_y \in \ell_p^*$, which means that we have a map

$$\begin{aligned} \varphi\colon \ell_q &\to \ell_p^* \\ y &\mapsto \varphi_y \end{aligned}$$

Note that φ is linear and bounded with $||\varphi|| \leq 1$.

Theorem 2.4

Let p, q, φ be as above. Then φ is an isometric isomorphism $\ell_q \to \ell_p^*$.

Proof. It remains to check that φ is isometric and surjective:

- φ is isometric

  Fix $y \in \ell_q$. WLOG $y \neq 0$. Define

$$x_n = \begin{cases} \dfrac{|y_n|^q}{y_n}, & y_n \neq 0 \\ 0, & y_n = 0 \end{cases}$$

  Observe that $\sum |x_n|^p = \sum |y_n|^{(q-1)p} \sum |y_n|^q = ||y||_q^q < \infty$, so $x \in \ell_p$ with $||x||_p^p = ||y||_q^q$. Since $y \neq 0$, we have $x \neq 0$, so $x/||x||_p \in B_{\ell_p}$. Note that

$$||\varphi_y|| \geq \varphi_y\left(\frac{x}{||x||_p}\right) = \frac{1}{||x||_p}\sum x_n y_n = \frac{||y||_q^q}{||y||_q^{q/p}} = ||y||_q.$$

  Hence, $||\varphi_y|| = ||y||_q$.

- φ is surjective

  Fix $f \in \ell_p^*$. Define $y_n = f(e_n), n \in \mathbb{N}$. Let $y = (y_n)$. For some fixed $N \in \mathbb{N}$, set

$$x_n = \begin{cases} \dfrac{|y_n|^q}{y_n}, & y_n \neq 0, n \leq N \\ 0, & \text{otherwise} \end{cases}$$

  Then $x = (x_n) \in \ell_p$, so

$$f(x) = \sum_{n=1}^N x_n f(x_n) = \sum_{n=1}^N x_n y_n = \sum_{n=1}^N |y_n|^2 \leq ||f||||x||_p$$

$$||x||_p = \left(\sum_{n=1}^N |x_n|^p\right)^{1/p} = \left(\sum_{n=1}^N |y_n|^{(q-1)p}\right)^{1/p} = \left(\sum_{n=1}^N |y_n|^q\right)^{1/p}$$

  Hence, $\displaystyle\sum_{n=1}^N |y_n|^q \leq ||f|| \left(\sum_{n=1}^N |y_n|^q\right)^{1/p}$, i.e.

$$\left(\sum_{n=1}^N |y_n|^q\right)^{1/q} \leq ||f||$$

  Let $N \to \infty$ to deduce that $y \in \ell_q$. Finally, observe that

$$\begin{aligned} & f(e_n) = y_n = \varphi_y(e_n)\ \forall\, n \in \mathbb{N} \\ \implies\ & f(x) = \varphi_y(x)\ \forall\, x \in \operatorname{span}\{e_n : n \in \mathbb{N}\} = c_{00} && \text{by linearity} \\ \implies\ & f(x) = \varphi_y(x)\ \forall\, x \in \overline{\operatorname{span}}\{e_n : n \in \mathbb{N}\} = \ell_p && \text{by continuity} \end{aligned}$$

  Thus, $f = \varphi_y$, so φ is surjective. ■

Remarks

- We also have $\ell_1^* \cong \ell_\infty$ and $c_0^* \cong \ell_1$. The proof also shows that $\ell_1 \hookrightarrow \ell_\infty^*$ isometrically. However, the proof of surjectivity breaks down since $\overline{\text{span}}\{e_n : n \in \mathbb{N}\}$ in ℓ_∞ in $c_0 \subsetneq \ell_\infty$.
- From the proof, we can show Corollary 2.3 holds for ℓ_p
- We've shown that $\ell_p, 1 \leq p \leq \infty$, is complete as they are dual spaces. For c_0, one simply has to show that c_0 is closed in ℓ_∞.

2.3 Bidual

Let X be a normed space. Then $X^{**} = (X^*)^* = \mathcal{B}(X^*, \mathbb{R})$ is the *bidual* or *second dual* of X.

For each $x \in X$, define the map

$$\begin{aligned} \hat{x} \colon X^* &\to \mathbb{R} \\ f &\mapsto f(x) \end{aligned}$$

Note that $\hat{x}$ is linear and bounded: $|\hat{x}(f)| = |f(x)| \leq ||f||||x||$. So $\hat{x} \in X^{**}$ with $||\hat{x}|| \leq ||x||$. Thus, we have

$$\begin{aligned} \hat{\ } \colon X &\to X^{**} \\ x &\mapsto \hat{x} \end{aligned}$$

This is linear: $\widehat{\lambda x + \mu y}(f) = f(\lambda x + \mu y) = \lambda f(x) + \mu f(y) = (\lambda \hat{x} + \mu \hat{y})(f)$.

For $x \neq 0$, let $f \in X^*$ be a norming functional at x. Then

$$\hat{x}(f) = f(x) = ||x|| \implies ||\hat{x}|| = ||x||$$

so the canonical map $X \to X^{**}, x \mapsto \hat{x}$ is an isometric embedding into X^{**}. If f is surjective, we say that X is *reflexive*.

2.4 Dual operators

Let X, Y be normed spaces and $T \in \mathcal{B}(X, Y)$. The *dual operator* T^* of T is the map

$$\begin{aligned} T^* \colon Y^* &\to X^* \\ g &\mapsto g \circ T \end{aligned}$$

By Proposition 1.6, $T^*(g) = g \circ T \in X^*$ and $||T^*(g)|| \leq ||g||||T||$, so T^* is well-defined. Moreover, it is clearly linear and bounded with $||T^*|| \leq ||T||$.

Remark. Note that $\langle \cdot, \cdot \rangle \colon X \times X^* \to \mathbb{R}$ is bilinear. Moreover, for $x \in X$ and $g \in Y^*$, we have $\langle x, T^*(g) \rangle = \langle T(x), g \rangle$.

It turns out that $||T^*|| = ||T||$:

$$||T^*|| = \sup_{g \in B_{Y^*}} ||T^* g|| = \sup_{g \in B_{Y^*}} \sup_{x \in B_X} |\langle x, T^*(g) \rangle| = \sup_{x \in B_X} \sup_{g \in B_{Y^*}} |\langle Tx, g \rangle| = \sup_{x \in B_X} ||Tx|| = ||T||,$$

where the penultimate equality follows from Corollary 2.3.

Example

Let $p, q \in (1, \infty)$ with $\frac{1}{p} + \frac{1}{q} = 1$. Consider the right-shift map $R \colon \ell_p \to \ell_p$. What is $R^* \colon \ell_p^* \to \ell_p^*$? Recall that $\ell_p^* \cong \ell_q$. Thought of as a map $\ell_q \to \ell_q$, it turns out that $R^* = L$, the left-shift map.

Now, let's note some properties of dual operators:

(1) $(\mathrm{Id}_X)^* = \mathrm{Id}_{X^*}$

(2) $(\lambda S + \mu T)^* = \lambda S^* + \mu T^*$ for all $S, T \in \mathcal{B}(X, Y)$ and all scalars λ, μ
Indeed, for $g \in Y^*$, $x \in X$,

$$\begin{aligned} \langle x, (\lambda S + \mu T)^* g\rangle &= \lambda(\lambda S + \mu T)x, g\rangle \\ &= \langle \lambda Sx + \mu Tx, g\rangle \\ &= \lambda\langle Sx, g\rangle + \mu\langle Tx, g\rangle \\ &= \lambda\langle x, S^* g\rangle + \mu\lambda x, T^* g\rangle \\ &= \lambda x, (\lambda S^* + \mu T^*)g\rangle \end{aligned}$$

Since x is arbitrary, $(\lambda S + \mu T)^* g = (\lambda S^* + \mu T*)g$ for all $g \in Y^*$, and we are done.

(3) $(ST)^* = T * S^*$ for all $T \in \mathcal{B}(X, Y)$ and all $S \in \mathcal{B}(Y, Z)$

$$\langle x, (ST)^* g\rangle = \langle STx, g\rangle = \langle S(Tx), g\rangle = \langle Tx, S^* g\rangle = \langle x, T^* S^* g\rangle$$

(4) Let $T \in \mathcal{B}(X, Y)$. We have $T^* \in \mathcal{B}(Y^*, X^*)$ and $T^{**} \in \mathcal{B}(X^{**}, Y^{**})$. The diagram

$$\begin{tikzcd} X \arrow[r, "T"] \arrow[d, "\hat{}"'] & Y \arrow[d] \\ X^{**} \arrow[r, "T^{**}"'] & Y^{**} \end{tikzcd}$$

commutes, i.e., $\hat{Tx} = T^{**}\hat{x}$ for all $x \in X$. For $x \in X, g \in Y^*$,

$$\langle g, T^{**}\hat{x}\rangle = \langle T^* g, \hat{x}\rangle = \langle x, T^* g\rangle = \langle Tx, g\rangle = \langle g, \widehat{Tx}\rangle$$

Remark. Properties (1) and (3) imply that $X \sim Y \implies X^* \sim Y^*$.