Mathematical Studies of Analysis

Based on lectures by Ian Tice
Notes taken by Runqiu Ye
Carnegie Mellon University

Spring 2025

Contents

1 Advanced topics in metric space theory

1.1 Baire category

Definition. Let X be a metric space.

1. We say that $E \subseteq X$ is nowhere dense if $(\overline{E})^\circ = \emptyset$.
2. We say that $E \subseteq X$ is meager in X if

$$E = \bigcup_{\alpha \in A} E_\alpha,$$

where A is a countable set and $E_\alpha \subseteq X$ is nowhere dense for every $\alpha \in A$.

Theorem. Prove that the following are equivalent for $E \subseteq X$:

1. E is nowhere dense
2. $\overline{E}$ is nowhere dense
3. $(\overline{E})^c$ is open and dense in X.

Proof. (a) $\implies$ (b). Suppose E is nowhere dense, then $(\overline{E})^\circ = \emptyset$. Note that the closure of $\overline{E}$ is just $\overline{E}$ itself. It follows that $\overline{E}$ is also nowhere dense.

(b) $\implies$ (c). Suppose $\overline{E}$ is nowhere dense. Note that $\overline{E}$ is closed, so $(\overline{E})^c$ is open. Let $x \in X$ be arbitrary. Since $\overline{E}$ is nowhere dense, $x \notin (\overline{E})^\circ$. This implies that for arbitrary $\varepsilon > 0$, we have $B(x, \varepsilon) \not\subset \overline{E}$. This is equivalent to $B(x, \varepsilon) \cap (\overline{E})^c \neq \emptyset$. Hence, $(\overline{E})^c$ is dense in X.

(c) $\implies$ (a). Suppose $(\overline{E})^c$ is dense in X. Let $x \in X$ and $\varepsilon > 0$ be arbitrary. It follows that $B(x, \varepsilon) \cap (\overline{E})^c \neq \emptyset$. This is equivalent to $B(x, \varepsilon) \not\subset \overline{E}$. Therefore, $(\overline{E})^\circ = \emptyset$ and E is nowhere dense. □

Theorem (Baire category thorem)**.** Let X be a complete metric space. Suppose that for each $n \in \mathbb{N}$, $U_n \subseteq X$ is open and dense in X. Prove that $\bigcap_{n=0}^{\infty} U_n$ is dense in X. Hint: use the shrinking closed set property.

Proof. Consider any $x \in X$ and arbitrary $\varepsilon > 0$, it suffices to show that $U_n \cap B(x, \varepsilon) \neq \emptyset$ for each $n \in \mathbb{N}$. Now inductively choosing a sequence $x_i \in X$ and $\varepsilon_i > 0$ such that for each $i \in \mathbb{N}$, $B[x_i, \varepsilon_i] \subset U_i$, $B[x_{i+1}, \varepsilon_i] \subset B[x_i, \varepsilon_i] \subset B(x, \varepsilon)$, and $\varepsilon_i < 2^{-i}\varepsilon$.

Since U_0 is dense in X, $B(x, \varepsilon) \cap U_0 \neq \emptyset$. Note that both U_0 and $B(x, \varepsilon)$ are open, so we can choose $x_0 \in B(x, \varepsilon) \cap U_0$ and $\varepsilon_0 > 0$ so small that $B[x_0, \varepsilon_0] \subset B(x, \varepsilon) \cap U_0$ and $\varepsilon_0 < \varepsilon$. Now suppose for $0 \leq i \leq n$, we have chosen $x_i \in X$ and $\varepsilon_i > 0$ such that $B[x_i, \varepsilon_i] \subset U_i$ and $\varepsilon_i < 2^{-i}\varepsilon$ for all $0 \leq i \leq n$, $B[x_{i+1}, \varepsilon_{i+1}] \subset B[x_i, \varepsilon_i]$ for all $0 \leq i < n$. Since U_{n+1} is dense in X, $B(x_n, \varepsilon_n) \cap U_{n+1} \neq \emptyset$. Note also both U_{n+1} and $B(x_n, \varepsilon_n)$ are open. Therefore, choose $x_{n+1} \in B(x_n, \varepsilon_n) \cap U_{n+1}$ and $\varepsilon_{n+1} > 0$ so small that $B[x_{n+1}, \varepsilon_{n+1}] \subset B(x_n, \varepsilon_n) \cap U_{n+1}$ and $\varepsilon_{n+1} < \frac{\varepsilon_n}{2}$. It follows that $B[x_{n+1}, \varepsilon_{n+1}] \subset U_{n+1}$ and $B[x_{n+1}, \varepsilon_{n+1}] \subset B[x_n, \varepsilon_n] \subset B(x, \varepsilon)$. Also, $\varepsilon < \frac{\varepsilon_n}{2} < 2^{-n-1}\varepsilon$. Now we have successfully constructing the desired sequence.

Since X is complete, $\bigcap_{n=0}^{\infty} B[x_n, \varepsilon_n] = \{z\}$ for some $z \in X$. Note that for each n, we have $z \in B[x_n, \varepsilon_n] \subset U_n$. Also, $z \in B[x_n, \varepsilon_n] \subset B(x, \varepsilon)$. Therefore, $z \in U_n \cap B(x, \varepsilon)$ for each $n \in \mathbb{N}$ and $\bigcap_{n=0}^{\infty} U_n$ is dense in X. □

Remark. An equivalent statement of the theorem is the following:
Let X be a complete metric space and $\{C_n\}$ a countable collection of closed subsets of X such that $X = \bigcup_{n \in \mathbb{N}} C_n$. Then at least one of the C_n contains an open ball.

1.2 Open Mapping Theorem

Linear surjections

Theorem (Open mapping theorem)**.** Let X, Y be Banach spaces over a common field and assume that $T \in \mathcal{L}(X;Y)$. Prove that the following are equivalent.

1. T is surjective.
2. There exists $\delta > 0$ such that $B_Y(0,\delta) \subseteq \overline{T(B_X(0,1))}$.
3. For every $\varepsilon > 0$ there exists $\delta > 0$ such that $B_Y(0,\delta) \subseteq T(B_X(0,\varepsilon))$.
4. T is an open map: if $U \subseteq X$ is open, then $T(U) \subseteq Y$ is open.
5. There exists $C \geq 0$ such that for each $y \in Y$ there exists $x \in X$ such that $Tx = y$ and
$$\|x\|_X \leq C\,\|y\|_Y\,.$$

HINT: Prove that $(1) \implies (2) \implies (3) \implies (4) \implies (5) \implies (1)$, keeping in mind the following suggestions.

1. For (1) $\implies$ (2): Study the sets $C_n = \overline{T(B_X(0,n))} \subseteq Y$ for $n \geq 1$.
2. For (2) $\implies$ (3): Prove that $\overline{T(B_X(0,1))} \subseteq T(B_X(0,3))$ by considering $y \in \overline{T(B_X(0,1))}$ and inductively constructing $\{x_j\}_{j=0}^\infty \subseteq X$ such that $\|x_j\|_X < 2^{-j}$ and $y - \sum_{j=0}^m Tx_j \in B_Y(0, 2^{-m-1}R)$ for all $m \in \mathbb{N}$.

Proof. (1) $\implies$ (2). Following the hint, for $n \geq 1$ let $C_n = \overline{T(B_X(0,n))}$. Then each of the C_n are closed. Since T is surjective, $Y = \bigcup_{n=1}^\infty C_n$. Suppose for contradiction that each C_n are nowhere dense. It then follows that C_n^c are dense in Y. By Baire Category Theorem, $\bigcap_{n=1}^\infty C_n^c$ is dense in Y. However, $\bigcap_{n=1}^\infty C_n^c = \left(\bigcup_{n=1}^\infty C_n\right)^c = \emptyset$, a contradiction. Therefore, at least one C_n is not nowhere dense. That is, there exists some $n \geq 1$, $\overline{T(B_X(0,n))}$ contains an open ball. However, this is the same set as $n\overline{T(B_X(0,1))}$. Therefore, $\overline{T(B_X(0,1))}$ contains an open ball $B_Y(y_0, 4r)$ for some $y_0 \in Y$ and $r > 0$.

Let $y_1 = Tx_1$ for some $x_1 \in B_Y(0,1)$ such that $\|y_0 - y_1\| < 2r$. It follows that $B_Y(y_1, 2r) \subset B_Y(y_0, 4r) \subset \overline{T(B_X(0,1))}$. For any $y \in Y$ such that $\|y\| < r$, we have

$$y = -\frac{1}{2}y_1 + \frac{1}{2}(2y + y_1) = -T\left(\frac{x_1}{2}\right) + \frac{1}{2}(2y + y_1).$$

However, notice that

$$\frac{1}{2}(2y + y_1) \subset \frac{1}{2}B_Y(y_1, 2r) \subset \frac{1}{2}\overline{T(B_X(0,1))} = \overline{T(B_X(0,\tfrac{1}{2}))}.$$

It follows that

$$y = -T\left(\frac{x_1}{2}\right) + \frac{1}{2}(2y + y_1) \in -T\left(\frac{x_1}{2}\right) + \overline{T(B_X(0,\tfrac{1}{2}))}.$$

Note that $-T(\frac{x_1}{2}) \in T(B_X(0,\frac{1}{2}))$. Therefore, $y \in \overline{T(B_X(0,1))}$. Since y is arbitrary with $\|y\| < r$, we have $B_Y(0,r) \subset \overline{T(B_X(0,1))}$.

(2) $\implies$ (3). Following the hint, we first show $\overline{T(B_X(0,1))} \subset T(B_X(0,3))$. By assumption, we have $B_Y(0,R) \subset \overline{T(B_X(0,1))}$ for some $R > 0$. It follows from homogeneity that for each $m \in \mathbb{N}$, we have

$$2^{-m}B_Y(0,R) = B_Y(0, 2^{-m}R) \subset 2^{-m}\overline{T(B_X(0,1))} = \overline{T(B_X(0,2^{-m}))}.$$

Let $y \in \overline{T(B_X(0,1))}$ and pick $x_0 \in X$ with $\|x\| < 1$ such that $\|y - Tx\| < 2^{-1}R$. Now suppose we have chosen x_j for $0 \leq j \leq m$ such that $\|x_j\| < 2^{-j}$ and $y - \sum_{j=0}^m Tx_j \in B_Y(0, 2^{-m-1}R)$ for all $m \in \mathbb{N}$. By the inclusion above, we can pick $x_{m+1} \in X$ with $\|x_{m+1}\| < 2^{-m-1}$ such that

$$\left\| y - \sum_{j=0}^m Tx_j - Tx_{m+1} \right\| = \left\| y - \sum_{j=0}^{m+1} Tx_j \right\| < 2^{-m-2}R.$$

Therefore, $y - \sum_{j=0}^{m+1} Tx_j \in B_Y(0, 2^{-m-2})R$. This completes the inductive construction, and we have found a sequence $\{x_j\}$ such that $\|x_j\| < 2^{-j}$ and $y - \sum_{j=0}^{m} Tx_j \in B_Y(0, 2^{-m-1}R)$ for each $m \in \mathbb{N}$. Note that

$$\sum_{j=0}^{\infty} \|x_j\| \leq \sum_{j=0}^{\infty} 2^{-j} = 2,$$

so $\sum_{j=0}^{\infty} x_j$ converges absolutely. Since X is Banach, $\sum_{j=0}^{\infty} x_j$ converges to some $x \in X$ with $\|x\| \leq 2$. Also, since $y - \sum_{j=0}^{m} Tx_j \in B_Y(0, 2^{-m-1}R)$, taking the limit where m approaches infinity we obtain

$$y = \sum_{j=0}^{\infty} Tx_j = T\left(\sum_{j=0}^{\infty} x_j\right) = Tx.$$

Therefore, $y \in T(B_X(0,3))$ and thus $\overline{T(B_X(0,1))} \subset T(B_X(0,3))$.

Now for every $\varepsilon > 0$, we have $\frac{\varepsilon}{3}\overline{T(B_X(0,1))} \subset \frac{\varepsilon}{3}T(B_X(0,3)) = T(B_X(0,\varepsilon))$. By assumption, there exists $\delta > 0$ such that $B_Y(0,\delta) \subset \overline{T(B_X(0,1))}$. Therefore,

$$B_Y\left(0, \frac{\delta\varepsilon}{3}\right) = \frac{\varepsilon}{3}B_Y(0,\delta) \subset \frac{\varepsilon}{3}\overline{T(B_X(0,1))} \subset T(B_X(0,\varepsilon)).$$

(3) $\implies$ (4). Let $U \subset X$ be open and $y \in T(U)$. There exists $x \in U$ such that $Tx = y$. Since U is open, there exists $\varepsilon > 0$ such that $B_X(x,\varepsilon) \subset U$. By assumption, there exists $\delta > 0$ such that $B_Y(0,\delta) \subset T(B_X(0,\varepsilon))$. It follows that

$$B_Y(y,\delta) = y + B_Y(0,\delta) \subset Tx + T(B_X(0,\varepsilon)) = T(x + B_X(0,\varepsilon)) \subset T(U).$$

Therefore, $T(U)$ is open and T is an open map.

(4) $\implies$ (5). Since T is an open map, $T(B_X(0,1))$ is open. Also, $T(0) = 0$ so there exists $r > 0$ such that $B_Y(0,r) \subset T(B_X(0,1))$. Now let $y \in Y$. Then, $\frac{r}{2\|y\|}y \in B_Y(0,r)$ and there exists $x \in B_X(0,1)$ such that $Tx = \frac{r}{2\|y\|}y$. It follows that

$$T\left(\frac{2\|y\|}{r}x\right) = y,$$

and since $x \in B_X(0,1)$,

$$\left\|\frac{2\|y\|}{r}x\right\| = \frac{2\|y\|\|x\|}{r} < \frac{2}{r}\|y\|.$$

Letting $C = \frac{2}{r}$ completes the proof.

(5) $\implies$ (1). Since for each $y \in Y$ there exists $x \in X$ such that $Tx = y$, T is surjective. □

Linear homeomorphisms, norm equivalence, and closed graphs

Theorem. Let X and Y be Banach spaces and suppose that $T \in \mathcal{L}(X,Y)$ is a bijection. Prove that $T^{-1} \in \mathcal{L}(Y,X)$, and in particular T is a linear (and thus bi-Lipschitz) homeomorphism.

Proof. Since $T \in \mathcal{L}(X,Y)$ is a bijection, T is a surjection. It follows that T is an open map. In particular, for any $U \subset X$ open, $T(U) = (T^{-1})^{-1}(U)$ is open. Therfore, T^{-1} is continuous and thus T is a linear homeomorphism. □

Theorem. Let X be a vector space that is complete when equipped with both of the norms $\|\cdot\|_1$ and $\|\cdot\|_2$. Prove that if there exists a constant $C_1 > 0$ such that $\|x\|_2 \leq C_1\|x\|_1$ for all $x \in X$, then there exists a constant $C_0 > 0$ such that $C_0\|x\|_1 \leq \|x\|_2 \leq C_1\|x\|_1$ for all $x \in X$.

Proof. Let $T : X_1 \to X_2$, where X_1 and X_2 are X equipped with norms $\|\cdot\|_1$ and $\|\cdot\|_2$, respectively, be the identity map. Then for any $x \in X$ with $\|x\|_1 = 1$, we have

$$\|Tx\|_2 = \|x\|_2 \leq C_1 \|x\|_1 = C_1.$$

Therefore, $T \in \mathcal{L}(X_1, X_2)$. T is also surjective. Therefore, there exists a constant $C \geq 0$ such that each $\|x\|_1 \leq C \|x\|_2$. Hence, for each $x \in X$

$$\frac{1}{C} \|x\|_1 \leq \|x\|_2 \leq C_1 \|x\|_1 .$$

Letting $C_0 = \frac{1}{C}$ completes the proof. □

Theorem. Let X and Y be Banach spaces and let $T : X \to Y$ be linear (just the algebraic condition). Prove that the following are equivalent

1. T is continuous, i.e. $T \in \mathcal{L}(X; Y)$.
2. The graph of T, $\Gamma(T) = \{(x, Tx) : x \in X\} \subseteq X \times Y$, is closed in $X \times Y$, where $X \times Y$ is endowed with any of the usual p-norms.

Proof. (a) $\implies$ (b). Let $\{(x_n, Tx_n)\}$ be a convergent sequence in $\Gamma(T)$. Since X is Banach, $x_n \to x$ for some $x \in X$. Since $T \in \mathcal{L}(X; Y)$, we have

$$\lim_{n\to\infty} Tx_n = T\left(\lim_{n\to\infty} x_n\right) = Tx.$$

Therefore, $(x_n, Tx_n) \to (x, Tx) \in \Gamma(T)$, and thus $\Gamma(T)$ is closed.

(b) $\implies$ (a). Let $\pi_1 : \Gamma(T) \to X$ and $\pi_2 : \Gamma(T) \to Y$ by $\pi_1(x, Tx) = x$ and $\pi_2(x, Tx) = Tx$. Since $\Gamma(T)$ is a closed in Banach space Y, $\Gamma(T)$ is Banach space. It is clear that both π_1 and π_2 are bounded linear maps. Moreover, π_1 is a bijection. It follows that $S = \pi_1^{-1}$ is a bounded linear map. Therefore, $T = \pi_2 \circ S$ is a bounded linear map. □

Linear injections with closed range

Theorem. Let X and Y be Banach spaces and $T \in \mathcal{L}(X, Y)$. Prove the following are equivalent.

1. T is injective and $\mathrm{range}(T)$ is closed.
2. $T : X \to \mathrm{range}(T)$ is a linear homeomorphism.
3. There exists $C \geq 0$ such that $\|x\|_X \leq C \|Tx\|_Y$ for all $x \in X$.

HINT: Prove that $(1) \implies (2) \implies (3) \implies (1)$.

Proof. (1) $\implies$ (2). If T is injective and $\mathrm{range}(T)$ is closed, then $\Gamma(T) = \{(x, Tx) : x \in X\}$ is closed in $X \times Y$. Therefore, $T : X \to \mathrm{range}(T)$ is a bounded linear map. Since T is injective, this map is actually bijective from X to $\mathrm{range}(T)$. Therefore, T is a linaer homeomorphism.

(2) $\implies$ (3). Since T is a bijective bounded linear map, from X to $\mathrm{range}(T)$. There exists a contant $C \geq 0$ such that for each $y \in \mathrm{range}(T)$ there exists a unique $x \in X$ such that $Tx = y$ and $\|x\| \leq C \|y\| = C \|Tx\|$. Since T is a bijection, $\|x\| \leq C \|Tx\|$ for all $x \in X$.

(3) $\implies$ (1). Let $x \in X$ be such that $Tx = 0$. It follows that $\|x\| \leq C \|Tx\| = 0$. Therefore, $x = 0$ and T is injective. To show that $\mathrm{range}(T)$ is closed, consider a convergent sequence $\{y_n\} \subset \mathrm{range}(T)$ with $y_n = Tx_n$. Since for any $n, m \in \mathbb{N}$ we have

$$\|x_n - x_m\| \leq C \|T(x_n - x_m)\| = C \|y_n - y_m\| ,$$

$\{x_n\}$ is Cauchy. Since X is Banach, $x_n \to x$ for some $x \in X$. Therefore, for all $n \in \mathbb{N}$ we have

$$\|y_n - Tx\| = \|T(x_n - x)\| \leq \|T\| \|x_n - x\| ,$$

and $y_n \to Tx$. Hence, $\mathrm{range}(T)$ is closed and the proof is complete. □

Theorem. Let X and Y be Banach spaces over a common field. Then, the following subsets of $\mathcal{L}(X;Y)$ are open:

1. $\{T \in \mathcal{L}(X;Y) : T \text{ is surjective}\}$,
2. $\{T \in \mathcal{L}(X;Y) : T \text{ is injective with closed range}\}$,
3. $\mathcal{H}(X;Y) = \{T \in \mathcal{L}(X;Y) : T \text{ is a homeomorphism}\}$.

Proof. 1. Let $T \in \mathcal{L}(X;Y)$ be surjective. By open mapping theorem, there is $\delta > 0$ such that $B_Y(0,\delta) \subset TB_X(0,1)$. By homogeneity we have $B_Y(0,r) \subset TB_X(0,\alpha r)$ for all $r > 0$ where $\alpha = \delta^{-1}$. Now let $S \in \mathcal{L}(X;Y)$ be such that $\|T - S\| < \beta < (2\alpha)^{-1}$. Claim S is surjective.

Let $y \in Y$, inductively construct sequences $\{x_n\}$ and $\{y_n\}$. First let $y_0 = y$. Then, $\|y_0\| \in B(0, 2\|y_0\|)$. Select $x_0 \in X$ be such that $Tx_0 = y_0$ and $\|x_0\| \leq 2\alpha \|y_0\|$. Suppose we have selected y_i, x_i for $0 \leq i \leq n$. Set $y_{n+1} = y_n - Sx_n$ and select x_{n+1} be such that $Tx_{n+1} = y_{n+1}$ and $\|x_{n+1}\| \leq 2\alpha \|y_{n+1}\|$. Then, we have

$$\|y_{n+1}\| = \|Tx_n - Sx_n\| \leq \|T - S\| \|x_n\| < 2\alpha\beta \|y_n\|$$

and

$$\|x_{n+1}\| = 2\alpha \|y_{n+1}\| \leq 2\alpha \|T - S\| \|x_n\| < 2\alpha\beta \|x_n\| .$$

Note that $2\alpha\beta < 1$ and X is Banach, define

$$x = \sum_{n=0}^{\infty} x_n = \lim_{N\to\infty} \sum_{n=0}^{N} x_n.$$

Also note that $\lim_{n\to\infty} y_n = 0$. It follows that

$$Sx = \sum_{n=0}^{\infty} Sx_n = \sum_{n=0}^{\infty} (y_n - y_{n+1}) = y_0 - \lim_{n\to\infty} y_{n+1} = y.$$

Therefore S is surjective and the set of surjective bounded linear maps are open.

2. Suppose $T \in \mathcal{L}(X;Y)$ is injective with closed range. Then, closed range theorem gives $C > 0$ such that $\|x\| \leq C\|Tx\|$ for all $x \in X$. Now supose $S \in \mathcal{L}(X;Y)$ is such that $\|T - S\| < (2C)^{-1}$. Claim that S is also injective with closed range. Indeed,

$$\begin{aligned}\|x\| &\leq C\|Tx\| \leq C\|Sx\| + C\|(T-S)x\| \\ &\leq C\|Sx\| + \frac{1}{2}\|x\| .\end{aligned}$$

This shows that $\|x\| \leq 2C\|Sx\|$ for all $x \in X$. By closed range theorem, S is injective with closed range. This implies that the set of injective bounded linear operator with closed range is open.

3. This directly follows from

$$\mathcal{H}(X;Y) = \{T \in \mathcal{L}(X;Y) : T \text{ is surjective}\} \cap \{T \in \mathcal{L}(X;Y) : T \text{ is injective with closed range}\} .$$

□

Theorem. Let X and Y be Banach spaces over a common field. Then the following holds.

1. The sets

$$\mathcal{L}_R(X;Y) = \{T \in \mathcal{L}(X;Y) : \text{there exists } S \in \mathcal{L}(Y;X) \text{ such that } ST = I_X\}$$

and

$$\mathcal{L}_L(X;Y) = \{T \in \mathcal{L}(X;Y) : \text{there exists } S \in \mathcal{L}(Y;X) \text{ such that } TS = I_Y\}$$

are open.

2. The following inclusion holds:

$$\mathcal{L}_L(X;Y) \subset \{T \in \mathcal{L}(X;Y) : T \text{ is surjective}\}$$

   and

$$\mathcal{L}_R(X;Y) \subset \{T \in \mathcal{L}(X;Y) : T \text{ is injective with closed range}\}.$$

3. The sets $\mathcal{L}_L(X;Y) \setminus \mathcal{L}_R(X;Y)$ and $\mathcal{L}_R(X;Y) \setminus \mathcal{L}_L(X;Y)$ are open.

Proof. 1. Let $T_0 \in \mathcal{L}_R$ and $S_0 \in \mathcal{L}(Y;X)$ be such that $T_0 S_0 = I_Y$. Note that $I_X \in \mathcal{H}(X)$ and when $\|P\| < 1$ for $P \in \mathcal{L}(X)$, we have $I_X + P \in \mathcal{H}(X)$. Suppose now $T \in \mathcal{L}(X;Y)$ and $\|T\| < \|S_0\|^{-1}$. It follows that $I_X + S_0 T \in \mathcal{H}(X)$. For such T, we then have

$$T_0 + T = T_0(I_X + S_0 T).$$

Also,

$$(T_0 + T)(I_X + S_0 T)^{-1} S_0 = T_0(I_X + S_0 T)(I_X + S_0 T)^{-1} S_0 = T_0 S_0 = I_Y.$$

Therefore, $T_0 + T \in \mathcal{L}_R$ for $T \in B(T_0, \|S_0\|^{-1})$ and $\mathcal{L}_R$ is open.

Now let $T_0 \in \mathcal{L}_L$ and $S_0 \in \mathcal{L}(Y;X)$ be such that $S_0 T_0 = I_X$. Again, for $T \in \mathcal{L}(X;Y)$ with $\|T\| < \|S_0\|^{-1}$, we have

$$T_0 + T = (I_X + T S_0) T_0.$$

and

$$S_0 (I_X + T S_0)^{-1} (T_0 + T) = I_X.$$

Therefore, $\mathcal{L}_R$ is also open.

2. Let $T \in \mathcal{L}_R$ and $S \in \mathcal{L}(Y;X)$ be such that $TS = I_Y$. Then for any $y \in Y$ let $x = Sy$. It follows that $Tx = TSy = y$. Also, $\|x\| \leq \|S\| \|y\|$ so the 4th item in open mapping theorem guarantees that T is surjective. Hence, $\mathcal{L}_L \subset \{T \in \mathcal{L}(X;Y) : T \text{ is surjective}\}$.

   Now let $T \in \mathcal{L}_L$ and $S \in \mathcal{L}(Y;X)$ such that $ST = I_X$. Now for any $x \in X$, we have $\|x\| = \|STx\| \leq \|S\| \|Tx\|$. Then the closed range theorem guarantees that T is injective with closed range. Hence, $\mathcal{L}_R \subset \{T \in \mathcal{L}_R(X;Y) : T \text{ is injective with closed range}\}$.

3. ***TO-DO***

□

2 Practice problems

Problem 1

Suppose $\omega : [0, \infty) \to [0, \infty]$ any function such that $\omega(x) = 0$ if and only if $x = 0$, ω continuous at 0, and ω is nondecreasing. For $f : X \to Z$ define

$$[f]_\omega = \sup \left\{ \frac{d(f(x), f(y))}{\omega(d(x, y))} : x, y \in X, x \neq y \right\}$$

and the space

$$C^{0,\omega}(X; Z) = \{ f : X \to Z \mid [f]_\omega < \infty \}.$$

1. Prove that $C^{0,\omega}(X; Z) \subset C^0(X; Z)$.

   Proof. Let $x \in X$ and $\varepsilon > 0$. It follws that for any $x \neq y$ we have

   $$d(f(x), f(y)) \leq [f]_\omega \omega(d(x, y)).$$

   Since $\omega(0) = 0$, ω continuous at 0, and ω is nondecreasing, we can find $\delta > 0$ such that $0 \leq t < \delta$ implies $0 \leq \omega(t) < \varepsilon$. Therefore, $d(x, y) < \delta$ implies $d(f(x), f(y)) < \varepsilon[f]_\omega$. Since $[f]_\omega < \infty$, f is continuous and $C^{0,\omega}(X; Z) \subset C^0(X; Z)$. $\square$

2. Suppose Z Banach. Show that $\|f\|_{C^{0,\omega}} = \|f\|_{C^0} + [f]_\omega$ is a norm on $C_b^{0,\omega}(X; Z) = C_b^0(X; Z) \cap C^{0,\omega}(X; Z)$, and that $C_b^{0,\omega}(X; Z)$ is complete with respect to this norm.

   Proof. It is easy to show that $\|\cdot\|_{C^{0,\omega}}$ is indeed a norm on $C_b^{0,\omega}(X; Z)$. Now we show that $C_b^{0,\omega}(X; Z)$ is complete with respect to this norm. Suppose $\{f_n\} \subset C_b^{0,\omega}$ Cauchy. Then it is also Cauchy in C_b^0. Therefore there is $f \in C_b^0$ such that $f_n \to f$ under C^0 norm. Remain to show $[f - f_n]_\omega \to 0$. Let $x, y \in X$ and $x \neq y$ and $m, n \geq N$ implies $[f_m - f_n]_\omega < \varepsilon$. Then,

   $$\frac{\|f_m(x) - f_m(y) - f_n(x) + f_n(y)\|_Z}{\omega(d(x, y))} < \varepsilon.$$

   Take $m \to \infty$ and take supremum of all $x, y \in X$ with $x \neq y$ completes the proof. $\square$

3. Suppose that X is compact and $d \in \mathbb{N}$, show that $B_{C^{0,\omega}(X;\mathbb{R}^d)}[0, 1] \subset C^0(X; \mathbb{R}^d)$ is compact.

4. Suppose X compact and infinte, and $d \in \mathbb{N}$. Show that $B_{C^{0,\omega}}[0, 1] \subset C^{0,\omega}$ is not compact. Conclude that $\mathrm{id} : (C^{0,\omega}, \|\cdot\|_{C^0}) \to (C^{0,\omega}, \|\cdot\|_{C^{0,\omega}})$ is not continuous. Also conclude that $(C^{0,\omega}, \|\cdot\|_{C^0})$ is not complete.

5. Another way to see this last fact is to first prove $C^{0,\omega}(X; \mathbb{R}^d)$ is a strict subset of $C^0(X; \mathbb{R}^d)$. It is helpful to study the sets $E_n = \left\{ f \in C^0(X; \mathbb{R}^d) : [f]_\omega \leq n \right\}$. Show that $C^{0,\omega}(X; \mathbb{R})$ is dense in $C^0(X; \mathbb{R})$. Use this to show that $C^{0,\omega}(X; \mathbb{R}^d)$ is dense in $C^0(X; \mathbb{R})$, and conclude $(C^{0,\omega}(X; \mathbb{R}^d), \|\cdot\|_{C^0})$ is not complete.