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A Function-Space Tour of Data Science: Banach Spaces and Sparse Methods

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1 Dual Spaces and Predual Spaces

Definition 1.1 (Dual space)**.** Let $\mathcal{F}$ be a normed space. The *(continuous) dual space* of $\mathcal{F}$ is denoted by $\mathcal{F}'$ and is the space of continuous linear functionals on $\mathcal{F}$. We write the canonical pairing as $\langle \cdot, \cdot \rangle : \mathcal{F} \times \mathcal{F}' \to \mathbb{R}$, i.e., if $f \in \mathcal{F}$ and $g \in \mathcal{F}'$, $\langle f, g \rangle = g[f]$.

Definition 1.2 (Bidual and canonical embedding)**.** The *bidual* is $\mathcal{F}'' \coloneqq (\mathcal{F}')'$. There is a canonical linear map $\iota : \mathcal{F} \to \mathcal{F}''$ defined by

$$(\iota(f))(g) \coloneqq g[f] = \langle f, g \rangle, \quad g \in \mathcal{F}'. \tag{1}$$

Remark 1.3. We always have that $\|\iota(f)\|_{\mathcal{F}''} = \|f\|_{\mathcal{F}}$ (so ι is an isometry). In particular, we can always identify $\mathcal{F} \subset \mathcal{F}''$. If ι is onto, we say $\mathcal{F}$ is *reflexive* and we can identify $\mathcal{F} = \mathcal{F}''$.

Definition 1.4 (Dual norm)**.** For $g \in \mathcal{F}'$, we define the *dual norm* as

$$\|g\|_{\mathcal{F}'} \coloneqq \sup_{\substack{f \in \mathcal{F} \\ \|f\|_{\mathcal{F}} \leq 1}} |\langle f, g \rangle|. \tag{2}$$

When endowed with this norm, the dual space $\mathcal{F}'$ is a Banach space.

Definition 1.5 (Predual)**.** A Banach space $\mathcal{X}$ is a *predual* of a Banach space $\mathcal{F}$ if $\mathcal{F} = \mathcal{X}'$ (isometrically). In this case we write the pairing as $\langle g, f \rangle$ for $g \in \mathcal{X}$ and $f \in \mathcal{F} = \mathcal{X}'$.

Remark 1.6. Not every Banach space admits a predual. For example, $L^1(\mathbb{R})$ has no predual.

Definition 1.7 (Strong and weak convergence)**.** Let $\mathcal{F}$ be a Banach space. A sequence $\{f_n\}_{n \in \mathbb{N}} \subset \mathcal{F}$ converges *strongly* (in norm) to $f \in \mathcal{F}$ if

$$\|f_n - f\| \to 0 \text{ as } n \to \infty.$$

A sequence $\{f_n\}_{n \in \mathbb{N}} \subset \mathcal{F}$ converges *weakly* to $f \in \mathcal{F}$ if

$$\langle f_n, g \rangle \to \langle f, g \rangle \text{ as } n \to \infty \text{ for all } g \in \mathcal{F}'.$$

Remark 1.8. The weak topology is still typically too fine for closed and bounded sets to be compact.

Definition 1.9 (Weak* convergence)**.** Let $\mathcal{F}$ be a Banach space such that $\mathcal{F} = \mathcal{X}'$ is a dual space with predual $\mathcal{X}$. A sequence $\{f_n\}_{n \in \mathbb{N}} \subset \mathcal{F}$ converges *weak** to $f \in \mathcal{F}$ if

$$\langle g, f_n \rangle \to \langle g, f \rangle \text{ as } n \to \infty \text{ for all } g \in \mathcal{X}. \tag{3}$$

Fact 1.10. *If $\mathcal{H}$ is a Hilbert space, then the weak and weak* topologies coincide (after identifying $\mathcal{H} = \mathcal{H}'$ via the Riesz Representation Theorem). More generally, if $\mathcal{F}$ is reflexive, then the weak and weak* coincide (by the identification $\mathcal{F} = \mathcal{F}''$).*

2 Banach–Alaoglu and Dixmier–Ng Theorems and Compactness

Theorem 2.1 (Banach–Alaoglu)**.** *Let $\mathcal{X}$ be a Banach space and let $\mathcal{F} = \mathcal{X}'$. Then the closed unit ball*

$$B_{\mathcal{F}} \coloneqq \{f \in \mathcal{F} : \|f\|_{\mathcal{F}} \leq 1\} \tag{4}$$

is compact in the weak topology on $\mathcal{F}$ (induced by $\mathcal{X}$).*

Remark 2.2. For optimization over dual Banach spaces, the weak* topology is often the "correct" topology to work with.

Theorem 2.3 (Dixmier–Ng)**.** *Let $\mathcal{F}$ be a normed space and let τ be a locally convex Hausdorff topology on $\mathcal{F}$. The following are equivalent:*

(1) The closed unit ball $B_{\mathcal{F}}$ is τ-compact.

(2) There exists a Banach space $\mathcal{X}$ such that $\mathcal{F} = \mathcal{X}'$.

Remark 2.4. The Dixmier–Ng establishes a fundamental impossibility result: If a Banach space does not have a predual, there does not exist any "reasonable" topology such that its closed unit ball is compact.

3 Riesz–Markov–Kakutani Representation Theorem

Theorem 3.1 (Riesz–Markov–Kakutani)**.** *Let Ξ be a compact (resp. locally compact) Hausdorff space. Let $C(\Xi)$ (resp. $C_0(\Xi)$) denote continuous real-valued functions on Ξ (continuous real-valued functions on Ξ vanishing at infinity) endowed with the L^∞-norm. Then, $C(\Xi)' = \mathcal{M}(\Xi)$ (resp. $C_0(\Xi)' = \mathcal{M}(\Xi)$), where $\mathcal{M}(\Xi)$ is the space of finite (signed) Radon measures on Ξ.*

4 Fisher–Jerome Theorem

Let $\varphi : \Omega \times \Xi \to \mathbb{R}$ be such that for each x, $\varphi(x, \cdot)$ is in $C(\Xi)$ (resp. $C_0(\Xi)$) when Ξ is a compact (resp. locally compact) Hausdorff space. Define the notation $\varphi_\xi(x) \coloneqq \varphi(x, \xi)$. Furthermore, define

$$f_\nu(x) \coloneqq \int_\Xi \varphi_\xi(x) \,\mathrm{d}\nu(\xi). \tag{5}$$

Theorem 4.1. *If, for every $y \in \mathbb{R}$, the loss function $\mathcal{L}(y, \cdot) : \mathbb{R} \to \mathbb{R} \cup \{+\infty\}$ is lower semicontinuous (l.s.c.), $\mathcal{L}(y, 0) < +\infty$,[1] and bounded from below, the solution set*

$$S \coloneqq \operatorname*{arg\,min}_{\nu \in \mathcal{M}(\Xi)} \left\{ J(\nu) = \sum_{i=1}^{n} \mathcal{L}(y_i, f_\nu(x_i)) + \lambda \|\nu\|_{\mathcal{M}} \right\}, \quad \lambda > 0, \tag{6}$$

is nonempty. Furthermore, there always exists a solution $\nu^\star \in S$ that yields the representation

$$f_{\nu^\star} = \sum_{k=1}^{K} v_k \varphi_{\xi_k}, \quad K \leq n. \tag{7}$$

Proof. Since $\mathcal{L}(y, \cdot)$ is l.s.c., J is weak* l.s.c. Indeed,

- the functional $\nu \mapsto f_\nu(x)$ is weak* continuous for all $x \in \Omega$ since

$$f_\nu(x) = \int_\Xi \varphi(x, \xi) \,\mathrm{d}\nu(\xi) = \langle \varphi(x, \cdot), \nu \rangle \tag{8}$$

  and $\varphi(x, \cdot) \in C(\Xi)$ (resp. $C_0(\Xi)$) when Ξ is compact (resp. locally compact).

[1]This ensures that J is proper on $\mathcal{M}(\Xi)$.

- the norm $\|\cdot\|_{\mathcal{M}}$ is weak* l.s.c. on $\mathcal{M}(\Xi)$ since

$$\|\nu\|_{\mathcal{M}} = \sup_{\substack{\varphi \in C(\Xi) \text{ or } C_0(\Xi) \\ \|\varphi\|_L^\infty = 1}} |\langle \varphi, \nu \rangle|, \tag{9}$$

where we recall that the sup of weak* continuous functions is weak* l.s.c.

Since $\mathcal{L}(y, \cdot)$ is bounded from below, J is coercive. Indeed, J is the sum of something bounded from below and something coercive (all norms are obviously coercive). Since J is weak* l.s.c., it has weak* closed sublevel sets. Furthermore, since J is coercive, it has bounded sublevel sets. Thus, it has weak* compact sublevel sets and hence minimizers exist.

Let $\widehat{\nu} \in S$ be any minimizer and set $z_i \coloneqq f_{\widehat{\nu}}(x_i)$ for $i = 1, \ldots, n$. Consider the auxiliary problem

$$\min_{\nu \in \mathcal{M}(\Xi)} \|\nu\|_{\mathcal{M}} \quad \text{s.t.} \quad f_\nu(x_i) = z_i, i = 1, \ldots, n. \tag{10}$$

Its feasible set is nonempty (it contains $\widehat{\nu}$) Let S_z be its solution set. Because the constraint set is weak*-closed and the objective is weak* l.s.c. with weak* compact sublevel sets, S_z is nonempty, weak* compact, and convex. Thus, S_z has extreme points by the Krein–Milman theorem. Finally, any solution to (10) is a solution to the original problem (6). Thus, it suffices to show that there exists a solution to (10) that is supported on at most n points.

Let $\nu^\star$ be an extreme point of S_z. We claim that $\nu^\star$ is supported on at most n points. Assume for contradiction that $\nu^\star$ is supported on more than n points. Let $\nu^\star = \nu^\star_+ - \nu^\star_-$ be its Jordan decomposition and let $\Xi = P \sqcup N$ be a Hahn decomposition for $\nu^\star$ (so $\nu^\star \geq 0$ on P and $\nu^\star \leq 0$ on N). Since $|\nu^\star|(\Xi) > 0$ and $\operatorname{supp}(|\nu^\star|)$ has more than n points, we can find pairwise disjoint Borel sets $A_1, \ldots, A_{n+1} \subset \Xi$ such that $|\nu^\star|(A_j) > 0$ for each j, and each A_j lies entirely in P or entirely in N. Finally, define $A_0 = \Xi \setminus \bigcup_{j=1}^{n+1} A_j$. Define the restricted signed measures

$$\nu_j \coloneqq \nu^\star|_{A_j}, \quad j = 0, \ldots, n+1. \tag{11}$$

Then, $\nu^\star = \sum_{j=0}^{n+1} \nu_j$, and the signed measures $\nu_0, \nu_1, \ldots, \nu_{n+1}$ are pairwise mutually singular.

For each j, define $b_j \in \mathbb{R}^n$ by

$$(b_j)_i \coloneqq f_{\nu_j}(x_i), \quad i = 1, \ldots, n. \tag{12}$$

Since we have $n+1$ vectors in $\mathbb{R}^n$, they are linearly dependent. Thus, there exist scalars $a_1, \ldots, a_{n+1}$, not all zero, such that $\sum_{j=1}^{n+1} a_j b_j = 0$. Let

$$\mu \coloneqq \sum_{j=1}^{n+1} a_j \nu_j. \tag{13}$$

Then for each i,

$$f_\mu(x_i) = \sum_{j=1}^{n+1} a_j f_{\nu_j}(x_i) = \sum_{j=1}^{n+1} a_j (b_j)_i = 0, \tag{14}$$

so $\nu^\star + t\mu$ satisfies the constraints in (10) for all $t \in \mathbb{R}$.

Because each ν_j has constant sign, there exists $\varepsilon > 0$ such that $1 \pm \varepsilon a_j \geq 0$ for all j (e.g., take $\varepsilon \leq \min_{a_j \neq 0} 1/(2|a_j|)$). For such an ε,

$$\nu^\star \pm \varepsilon\mu = \nu_0 + \sum_{j=1}^{n+1} (1 \pm \varepsilon a_j)\, \nu_j, \tag{15}$$

and no sign flips occur within each A_j. Consequently, for $t \in [-\varepsilon, \varepsilon]$ the map $t \mapsto \|\nu^\star + t\mu\|_{\mathcal{M}}$ is affine:

$$\|\nu^\star + t\mu\|_{\mathcal{M}} = \|\nu_0\|_{\mathcal{M}} + \sum_{j=1}^{n+1} \|(1 + ta_j)\nu_j\|_{\mathcal{M}} = \|\nu_0\|_{\mathcal{M}} + \sum_{j=1}^{n+1} (1 + ta_j)\|\nu_j\|_{\mathcal{M}}. \tag{16}$$

where we used the fact that the A_j are disjoint. But $\nu^\star$ minimizes $\nu \mapsto \|\nu\|_{\mathcal{M}}$ over the feasible affine set, so $t = 0$ is a minimizer of this affine function on $[-\varepsilon, \varepsilon]$. Therefore its slope must be zero, i.e.,

$$\sum_{j=1}^{n+1} a_j \|\nu_j\|_{\mathcal{M}} = 0, \tag{17}$$

and hence

$$\|\nu^\star \pm \varepsilon\mu\|_{\mathcal{M}} = \|\nu^\star\|_{\mathcal{M}}. \tag{18}$$

Thus, $\nu^\star \pm \varepsilon\mu \in S_z$ and they are distinct (since $\mu \neq 0$). Thus,

$$\nu^\star = \frac{1}{2}(\nu^\star + \varepsilon\mu) + \frac{1}{2}(\nu^\star - \varepsilon\mu), \tag{19}$$

contradicting that $\nu^\star$ is an extreme point of S_z.

We conclude that $\nu^\star$ is supported on at most n points, i.e.,

$$\nu^\star = \sum_{k=1}^{K} v_k \delta_{\xi_k}, \quad K \leq n, \tag{20}$$

and therefore,

$$f_{\nu^\star} = \int_{\Xi} \varphi_\xi \, \mathrm{d}\nu^\star(\xi) = \sum_{k=1}^{K} v_k \varphi_{\xi_k}, \tag{21}$$

which completes the proof. □

Remark 4.2. The $\mathcal{M}$-norm is not strictly convex, so uniqueness of minimizers for (6) is hard to guarantee, just like finite-dimensional ℓ^1-minimization problems. In finite dimensions, compressed sensing gives conditions implying uniqueness. In infinite dimensions, various “off-the-grid” analogues exist which provide conditions for uniqueness using tools from convex duality.