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A DUALITY-BASED PROOF OF THE TRIANGLE INEQUALITY FOR THE WASSERSTEIN DISTANCES

FRANÇOIS GOLSE

ABSTRACT. This short note gives a proof of the triangle inequality based on the Kantorovich duality formula for the Wasserstein distances of exponent $p \in [1, +\infty)$ in the case of a general Polish space. In particular it avoids the “glueing of couplings” procedure used in most textbooks on optimal transport.

1. INTRODUCTION

Let (\mathcal{E}, d) be a Polish metric space (with metric denoted by d). The Wasserstein distances are a family of metrics defined on subsets of $\mathcal{P}(\mathcal{E})$, the set of Borel probability measures on \mathcal{E} . Specifically, for each $p \geq 1$, set

$$\mathcal{P}_p(\mathcal{E}) := \left\{ \mu \in \mathcal{P}(\mathcal{E}) \text{ s.t. } \int_{\mathcal{E}} d(x_0, x)^p \mu(dx) < \infty \right\}.$$

(Obviously, if the above condition is satisfied for one $x_0 \in \mathcal{E}$, it is satisfied for all $x_0 \in \mathcal{E}$ by the triangle inequality for the metric d and by convexity of the map $z \mapsto z^p$ on $(0, +\infty)$.) For all $\mu, \nu \in \mathcal{P}(\mathcal{E})$, a coupling of μ, ν is an element ρ of $\mathcal{P}(\mathcal{E} \times \mathcal{E})$ such that¹

$$\iint_{\mathcal{E} \times \mathcal{E}} (\phi(x) + \psi(y)) \rho(dxdy) = \int_{\mathcal{E}} \phi(x) \mu(dx) + \int_{\mathcal{E}} \psi(y) \nu(dy)$$

for all $\phi, \psi \in C_b(\mathcal{E})$ (the set of bounded continuous functions on \mathcal{E}). The set of couplings of μ, ν is denoted by $\mathcal{C}(\mu, \nu)$. (Notice that $\mathcal{C}(\mu, \nu)$ is nonempty since $\mu \otimes \nu \in \mathcal{C}(\mu, \nu)$.) The Wasserstein distance with exponent p between $\mu, \nu \in \mathcal{P}_p(\mathcal{E})$ is defined as

$$\mathcal{W}_p(\mu, \nu) := \left(\inf_{\rho \in \mathcal{C}(\mu, \nu)} \iint_{\mathcal{E} \times \mathcal{E}} d(x, y)^p \rho(dxdy) \right)^{1/p} < +\infty.$$

The Wasserstein distances are of considerable importance in the field of optimal transport, with applications to the calculus of variations, to statistics, to statistical mechanics, to machine learning, to cite only a few applications — see [8] for more examples. For instance, \mathcal{W}_p metrizes a variant of the weak convergence of probability measures in $\mathcal{P}_p(\mathcal{E})$: see Theorem 7.12 in [12], or Theorem 6.9 in [13].

Recently, analogues of the Wasserstein metric with exponent 2 have been defined in the quantum setting [4, 7]. Specifically, these analogues measure the difference between two density operators, i.e. nonnegative self-adjoint trace-class operators

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¹Since \mathcal{E} is separable, the Borel σ -algebra of $\mathcal{E} \times \mathcal{E}$ is the product of the Borel σ -algebra of \mathcal{E} with itself: see Proposition 2.4.2 in chapter I of [6].

with trace equal to one defined on a separable Hilbert space, which are the quantum analogue of phase-space probability measures in classical mechanics. These analogues of the Wasserstein distance of exponent 2 satisfy some variant of the triangle inequality (see Theorem 5.1 in [5] and formula (51) in [7]) but, at the time of this writing, whether the genuine triangle inequality is satisfied by these quantum Wasserstein (pseudo)metrics remains an open question.

If one returns to the classical setting, most references on optimal transport prove the triangle inequality for the Wasserstein distances by means of a procedure known as “glueing couplings” between Borel probability measures. Specifically, given $\lambda, \mu, \nu \in \mathcal{P}_p(\mathcal{E})$, pick $\rho_{12} \in \mathcal{C}(\lambda, \mu)$ and $\rho_{23} \in \mathcal{C}(\mu, \nu)$; the glueing procedure provides us with $\sigma \in \mathcal{P}(\mathcal{E} \times \mathcal{E} \times \mathcal{E})$ such that

$$\begin{aligned} & \iiint_{\mathcal{E} \times \mathcal{E} \times \mathcal{E}} (\Phi(x, y) + \Psi(y, z)) \sigma(dx dy dz) \\ &= \iint_{\mathcal{E} \times \mathcal{E}} \Phi(x, y) \rho_{12}(dx dy) + \iint_{\mathcal{E} \times \mathcal{E}} \Psi(y, z) \rho_{23}(dy dz) \end{aligned}$$

for all $\Phi, \Psi \in C_b(\mathcal{E} \times \mathcal{E})$. This is the key step in one proof of the triangle inequality for \mathcal{W}_p (see for instance [12, 1, 13, 2]). Once the probability measure σ has been constructed, the remaining part of the proof of the triangle inequality is a routine computation involving the Minkowski inequality. One proof of the existence of σ provided by the glueing procedure is based on disintegration of probability measures (see for instance Lemma 7.6 in [12] or Remark 5.3.3 in [1]). There exists another argument avoiding disintegration of measures, which is based on the Hahn-Banach theorem in the special case where \mathcal{E} is compact: see Exercise 7.9 in [12]. Still another proof of the triangle inequality uses an optimal transport map, when it exists: see [10]. An optimal transport map between the probability measures $\mu, \nu \in \mathcal{P}_p(\mathcal{E})$ is a Borel measurable map $T: \mathcal{E} \rightarrow \mathcal{E}$ such that²

$$T_{\#}\mu = \nu \quad \text{and} \quad \mathcal{W}_p(\mu, \nu) = \left(\int_{\mathcal{E}} d(x, T(x))^p \mu(dx) \right)^{1/p}$$

The existence and uniqueness of an optimal transport map that is the gradient of a convex function is known in the case where \mathcal{E} is a (finite-dimensional) Euclidean space, with Euclidean metric d , and μ is absolutely continuous³ with respect to the Lebesgue measure on \mathcal{E} : this is Brenier’s theorem (see Theorem 2.12 (ii) in [12]).

None of the ingredients mentioned above (existence of optimal transport maps, glueing of couplings) are known to have analogues in general in the quantum setting. In fact, a recent counterexample due to D. Serre [11] shows that the glueing procedure *cannot* be extended to the quantum setting for *arbitrary* couplings.

In view of all these obstructions, we propose still another proof of the triangle inequality for the Wasserstein distances, in the hope that a different approach could perhaps lead to a better understanding of the quantum case.

²We denote by $T_{\#}\mu$ the image of the probability measure μ by the map T , defined by

$$\int_{\mathcal{E}} \phi(y) T_{\#}\mu(dy) = \int_{\mathcal{E}} \phi(T(x)) \mu(dx), \quad \text{for all } \phi \in C_b(\mathcal{E}).$$

³In fact, it is enough to assume that $\mu(A) = 0$ for all Borel measurable $A \subset \mathcal{E}$ of Hausdorff codimension ≥ 1 .

2. KANTOROVICH DUALITY

First, we recall the Kantorovich duality for the Wasserstein distance \mathcal{W}_p .

Kantorovich Duality Theorem. Let (\mathcal{E}, d) be a Polish space, and let $p \geq 1$. For all $\mu, \nu \in \mathcal{P}_p(\mathcal{E})$

$$\mathcal{W}_p(\mu, \nu)^p = \sup_{a(x)+b(y) \leq d(x,y)^p} \left(\int_{\mathcal{E}} a(x)\mu(dx) + \int_{\mathcal{E}} b(y)\nu(dy) \right).$$

In this formula, it is equivalent to assume that the functions a and b belong to $C_b(\mathcal{E})$, or that $a \in L^1(\mathcal{E}, \mu)$ while $b \in L^1(\mathcal{E}, \nu)$, in which case $a(x) + b(y) \leq d(x, y)^p$ holds $\mu \otimes \nu$ -a.e.. (See for instance Theorem 1.3 in [12].)

Henceforth, in the latter case, we shall systematically normalize the pair (a, b) as follows: pick $a, b : \mathcal{E} \rightarrow \mathbf{R} \cup \{-\infty\}$ to be measurable representatives of the corresponding elements in $L^1(\mathcal{E}, \mu)$ and $L^1(\mathcal{E}, \nu)$ resp., together with a μ -negligible set $M \subset \mathcal{E}$ and a ν -negligible set $N \subset \mathcal{E}$ such that $a(x) + b(y) \leq d(x, y)^p$ holds for all $x \in M^c$ and all $y \in N^c$. Modifying a and b so that $a(x) = -\infty$ for all $x \in M$ and $b(y) = -\infty$ for all $y \in N$, we obtain in this way new measurable representatives of the same elements $L^1(\mathcal{E}, \mu)$ and $L^1(\mathcal{E}, \nu)$ as before, such that the inequality $a(x) + b(y) \leq d(x, y)^p$ holds for all $x, y \in \mathcal{E}$.

It will be convenient to define a notion of p -Legendre transform, as follows: for $f : \mathcal{E} \rightarrow \mathbf{R} \cup \{-\infty\}$, not identically equal to $-\infty$, set

$$f^{[p^*]}(y) := \inf_{x \in \mathcal{E}} (d(x, y)^p - f(x)), \quad y \in \mathcal{E}.$$

A function $g : \mathcal{E} \rightarrow \mathbf{R} \cup \{-\infty\}$ is said to be d^p -concave, if it is of the form $g = f^{[p^*]}$ for some $f : \mathcal{E} \rightarrow \mathbf{R} \cup \{-\infty\}$ that is not identically equal to $-\infty$.

Optimal Kantorovich Potentials. Under the same assumptions as in the Kantorovich duality theorem for \mathcal{W}_p , there exists a pair (a, b) of p -Legendre conjugate functions — i.e. $b = a^{[p^*]}$ and $a = b^{[p^*]}$ — such that $a \in L^1(\mathcal{E}, \mu)$ and $b \in L^1(\mathcal{E}, \nu)$, and

$$\mathcal{W}_p(\mu, \nu)^p = \int_{\mathcal{E}} a(x)\mu(dx) + \int_{\mathcal{E}} b(y)\nu(dy).$$

(See Remark 1.12, the double convexification trick (2.10), Remark 2.2 and Exercise 2.36 in [12].)

There are two particular cases of special interest, corresponding to $p = 1$ and $p = 2$.

Kantorovich-Rubinstein Duality Theorem. Let (\mathcal{E}, d) be a Polish space with metric d . Then, for all $\mu, \nu \in \mathcal{P}_1(\mathcal{E})$, it holds

$$\mathcal{W}_1(\mu, \nu) = \sup_{\text{Lip}(\phi) \leq 1} \left| \int_{\mathcal{E}} \phi(z)\mu(dz) - \int_{\mathcal{E}} \phi(z)\nu(dz) \right|.$$

(Indeed, one can check that $(\phi^{[1^*]})^{[1^*]} = -\phi^{[1^*]}$ is a contraction on \mathcal{E} : see Theorem 1.14 and its proof in [12].)

In the case $p = 2$, assuming that \mathcal{E} is a Euclidean space and $d(x, y) = |x - y|$ is its Euclidean metric, the notion of 2-Legendre duality is easily reduced to the classical notion of Legendre transform (as in §26 of [9], for instance). Indeed

$$g(y) = \inf_{x \in \mathcal{E}} (|x - y|^2 - f(x)) = |y|^2 + \inf_{x \in \mathcal{E}} (|x|^2 - 2x \cdot y - f(x))$$

if and only if

$$\frac{1}{2}(|y|^2 - g(y)) = \sup_{x \in \mathcal{E}} (x \cdot y - \frac{1}{2}(|x|^2 - f(x))).$$

In other words, defining $F(x) := \frac{1}{2}(|x|^2 - f(x))$ and $G(y) := \frac{1}{2}(|y|^2 - g(y))$, it holds

$$g = f^{[2^*]} \iff G = F^* \text{ (the Legendre transform of } F\text{)}.$$

3. A DUALITY-BASED PROOF OF THE TRIANGLE INEQUALITY FOR \mathcal{W}_2

In this section, we explain how to use the Kantorovich duality to prove that

$$\mathcal{W}_2(\lambda, \nu) \leq \mathcal{W}_2(\lambda, \mu) + \mathcal{W}_2(\mu, \nu)$$

for all $\lambda, \mu, \nu \in \mathcal{P}_2(\mathcal{E})$. This first result is a warm-up for the duality-based proof of the triangle inequality for \mathcal{W}_p in the case of an arbitrary exponent $p \in [1, +\infty)$. We recall that (\mathcal{E}, d) is a Polish space with metric denoted by d .

Pick 2-Legendre conjugate, optimal Kantorovich potentials for $\mathcal{W}_2(\lambda, \nu)$, denoted by α and γ . Thus

$$\alpha(x) = \inf_{z \in \mathcal{E}} (d(x, z)^2 - \gamma(z)), \quad \gamma(z) = \inf_{x \in \mathcal{E}} (d(x, z)^2 - \alpha(x));$$

besides $\alpha \in L^1(\mathcal{E}, \lambda)$ while $\gamma \in L^1(\mathcal{E}, \nu)$, and

$$\mathcal{W}_2(\lambda, \nu)^2 = \int_{\mathcal{E}} \alpha(x) \lambda(dx) + \int_{\mathcal{E}} \gamma(z) \nu(dz).$$

For each $\eta > 0$, set

$$(1) \quad \beta_\eta(y) := (1 + \frac{1}{\eta}) \inf_{z \in \mathcal{E}} \left(d(y, z)^2 - \frac{\gamma(z)}{1 + \frac{1}{\eta}} \right).$$

Obviously, the function

$$y \mapsto \beta_\eta(y) / (1 + \frac{1}{\eta})$$

is d^2 -concave, since $\gamma \in L^1(\mathcal{E}, \nu)$ is ν -a.e. finite.

Lemma 1. Under the assumptions above, it holds

$$\alpha(x) - \beta_\eta(y) \leq (1 + \eta) d(x, y)^2, \quad \text{for all } x, y \in \mathcal{E}.$$

Taking Lemma 1 for granted, we conclude the proof of the triangle inequality for \mathcal{W}_2 .

Proof of the triangle inequality for \mathcal{W}_2 . First observe that $\beta_\eta \in L^1(\mathcal{E}; \mu)$. Indeed,

$$\begin{aligned} |\beta_\eta(y)| &\leq (1 + \frac{1}{\eta}) d(y, z)^2 + |\gamma(z)| \\ &\leq (1 + \frac{1}{\eta}) (d(x_0, y) + d(x_0, z))^2 + |\gamma(z)| \\ &\leq 2(1 + \frac{1}{\eta}) (d(x_0, y)^2 + d(x_0, z)^2) + |\gamma(z)|, \end{aligned}$$

where x_0 is any point chosen in \mathcal{E} . Integrating both sides of this inequality with the measure $\mu \otimes \nu$, we find that

$$\int_{\mathcal{E}} |\beta_\eta(y)| \mu(dy) \leq 2(1 + \frac{1}{\eta}) \left(\int_{\mathcal{E}} d(x_0, y)^2 \mu(dy) + \int_{\mathcal{E}} d(x_0, z)^2 \nu(dz) \right) + \int_{\mathcal{E}} |\gamma(z)| \nu(dz)$$

so that $\beta_\eta \in L^1(\mathcal{E}, \mu)$ since $\mu, \nu \in \mathcal{P}_2(\mathcal{E})$ and $\gamma \in L^1(\mathcal{E}, \nu)$.

Since $\beta_\eta \in L^1(\mathcal{E}, \mu)$ and $\gamma \in L^1(\mathcal{E}, \nu)$ satisfy

$$\frac{\beta_\eta(y)}{1 + \frac{1}{\eta}} + \frac{\gamma(z)}{1 + \frac{1}{\eta}} \leq d(y, z)^2, \quad y, z \in \mathcal{E}$$

according to the definition (1) of β_η , the Kantorovich Duality Theorem implies that

$$(2) \quad \frac{1}{1+\frac{1}{\eta}} \int_{\mathcal{E}} \beta_\eta(y) \mu(dy) + \frac{1}{1+\frac{1}{\eta}} \int_{\mathcal{E}} \gamma(z) \nu(dz) \leq \mathcal{W}_2(\mu, \nu)^2.$$

On the other hand, the fact that $\alpha \in L^1(\mathcal{E}, \lambda)$ and $\beta_\eta \in L^1(\mathcal{E}, \mu)$, together with the inequality in Lemma 1 and the Kantorovich Duality Theorem, imply that

$$(3) \quad \frac{1}{1+\eta} \int_{\mathcal{E}} \alpha(x) \lambda(dx) - \frac{1}{1+\eta} \int_{\mathcal{E}} \beta_\eta(y) \mu(dy) \leq \mathcal{W}_2(\lambda, \mu)^2.$$

Multiplying both sides of (2) by $1 + \frac{1}{\eta}$ and both sides of (3) by $1 + \eta$, and adding each side of the resulting inequalities, we see that

$$\begin{aligned} \mathcal{W}_2(\lambda, \nu)^2 &= \int_{\mathcal{E}} \alpha(x) \lambda(dx) + \int_{\mathcal{E}} \gamma(z) \nu(dz) \\ &= \int_{\mathcal{E}} \alpha(x) \lambda(dx) - \int_{\mathcal{E}} \beta_\eta(y) \mu(dy) + \int_{\mathcal{E}} \beta_\eta(y) \mu(dy) + \int_{\mathcal{E}} \gamma(z) \nu(dz) \\ &\leq (1 + \eta) \mathcal{W}_2(\lambda, \mu)^2 + (1 + \frac{1}{\eta}) \mathcal{W}_2(\mu, \nu)^2. \end{aligned}$$

Assuming that $\lambda \neq \mu$, so that $\mathcal{W}_2(\lambda, \mu) > 0$, we pick $\eta := \mathcal{W}_2(\mu, \nu) / \mathcal{W}_2(\lambda, \mu)$ to find that

$$\begin{aligned} \mathcal{W}_2(\lambda, \nu)^2 &\leq \mathcal{W}_2(\lambda, \mu)^2 + \mathcal{W}_2(\mu, \nu)^2 + 2\mathcal{W}_2(\lambda, \mu)\mathcal{W}_2(\mu, \nu) \\ &= (\mathcal{W}_2(\lambda, \mu) + \mathcal{W}_2(\mu, \nu))^2. \end{aligned}$$

Otherwise, $\lambda = \mu$ and the triangle inequality is trivial. \square

It only remains to prove Lemma 1.

Proof of Lemma 1. We seek to bound

$$\begin{aligned} \alpha(x) - \beta_\eta(y) &= \inf_{z \in \mathcal{E}} (d(x, z)^2 - \gamma(z)) - (1 + \frac{1}{\eta}) \inf_{z \in \mathcal{E}} \left(d(y, z)^2 - \frac{\gamma(z)}{1 + \frac{1}{\eta}} \right) \\ &= \inf_{z \in \mathcal{E}} (d(x, z)^2 - \gamma(z)) - \inf_{z \in \mathcal{E}} \left((1 + \frac{1}{\eta}) d(y, z)^2 - \gamma(z) \right) \end{aligned}$$

Let $\epsilon > 0$; there exists $z_\epsilon \in \mathbf{R}^d$ such that

$$\begin{aligned} \inf_{z \in \mathcal{E}} \left((1 + \frac{1}{\eta}) d(y, z)^2 - \gamma(z) \right) &\leq \left((1 + \frac{1}{\eta}) d(y, z_\epsilon)^2 - \gamma(z_\epsilon) \right) \\ &< \inf_{z \in \mathcal{E}} \left((1 + \frac{1}{\eta}) d(y, z)^2 - \gamma(z) \right) + \epsilon. \end{aligned}$$

Then

$$\begin{aligned} \alpha(x) - \beta_\eta(y) &= \inf_{z \in \mathcal{E}} (d(x, z)^2 - \gamma(z)) - \inf_{z \in \mathcal{E}} \left((1 + \frac{1}{\eta}) d(y, z)^2 - \gamma(z) \right) \\ &\leq (d(x, z_\epsilon)^2 - \gamma(z_\epsilon)) - \inf_{z \in \mathcal{E}} \left((1 + \frac{1}{\eta}) d(y, z)^2 - \gamma(z) \right) \\ &< (d(x, z_\epsilon)^2 - \gamma(z_\epsilon)) - \left((1 + \frac{1}{\eta}) d(y, z_\epsilon)^2 - \gamma(z_\epsilon) \right) + \epsilon \\ &= d(x, z_\epsilon)^2 - (1 + \frac{1}{\eta}) d(y, z_\epsilon)^2 + \epsilon. \end{aligned}$$

But, for each $\eta > 0$, it holds

$$\begin{aligned} d(x, z_\epsilon)^2 &\leq (d(x, y) + d(y, z_\epsilon))^2 \\ &= d(x, y)^2 + d(y, z_\epsilon)^2 + 2d(x, y)d(y, z_\epsilon) \\ &\leq d(x, y)^2 + d(y, z_\epsilon)^2 + \eta d(x, y)^2 + \frac{1}{\eta} d(y, z_\epsilon)^2 \\ &= (1 + \eta)d(x, y)^2 + (1 + \frac{1}{\eta})d(y, z_\epsilon)^2. \end{aligned}$$

With the preceding inequality, we conclude that

$$\alpha(x) - \beta_\eta(y) \leq (1 + \eta)d(x, y)^2 + \epsilon,$$

and the desired inequality follows from letting $\epsilon \rightarrow 0^+$. \square

4. A DUALITY-BASED PROOF OF THE TRIANGLE INEQUALITY FOR \mathcal{W}_p WITH $1 \leq p < \infty$ AND $p \neq 2$

In this section, we use the Kantorovich duality to prove that

$$(4) \quad \mathcal{W}_p(\lambda, \nu) \leq \mathcal{W}_p(\lambda, \mu) + \mathcal{W}_p(\mu, \nu)$$

for all $p \geq 1$ and all $\lambda, \mu, \nu \in \mathcal{P}_2(\mathcal{E})$. We recall that (\mathcal{E}, d) is a Polish space with metric denoted by d .

The case $p = 1$ follows immediately from the formula for \mathcal{W}_1 in the Kantorovich-Rubinstein Duality Theorem. Henceforth, we assume therefore that

$$p > 1 \quad \text{and} \quad p \neq 2.$$

A careful inspection of the duality-based proof of the triangle inequality for \mathcal{W}_2 shows the importance of the inequality

$$(5) \quad (X + Y)^2 \leq (1 + \eta)X^2 + (1 + \frac{1}{\eta})Y^2$$

for all $X, Y \geq 0$ and all $\eta > 0$.

Our first task is therefore to seek a function $(0, +\infty) \ni \eta \mapsto f(\eta) \in (0, +\infty)$ such that

$$(X + Y)^p \leq (1 + \eta)X^p + (1 + f(\eta))Y^p, \quad X, Y \geq 0, \quad \eta > 0.$$

Obviously, only the case $X, Y > 0$ is of interest, so that, by homogeneity, this boils down to finding f such that

$$(Z^{1/p} + 1)^p \leq (1 + \eta)Z + 1 + f(\eta), \quad Z, \eta > 0,$$

where $Z = X^p/Y^p$.

Equivalently, the optimal $f(\eta)$ is found to be given by the formula

$$f(\eta) := \sup_{Z > 0} (-\eta Z - 1 - Z + (1 + Z^{1/p})^p).$$

One easily checks that the function $(0, +\infty) \ni Z \mapsto (1 + Z^{1/p})^p \in (0, +\infty)$ is concave for $p > 1$, since

$$\frac{d}{dZ}(1 + Z^{1/p})^p = p(1 + Z^{1/p})^{p-1} \frac{1}{p} Z^{\frac{1}{p}-1} = (Z^{-1/p} + 1)^{p-1}$$

defines a decreasing bijection from $(0, +\infty)$ to itself. Hence there exists a unique critical value of $Z > 0$ such that

$$\frac{d}{dZ}(-\eta Z - 1 - Z + (1 + Z^{1/p})^p) = -(\eta + 1) + (Z^{-1/p} + 1)^{p-1} = 0,$$

which is

$$Z^{1/p} := \frac{1}{(\eta + 1)^{1/(p-1)} - 1},$$

and f is given by the formula

$$\begin{aligned} f(\eta) &:= \left(1 + \frac{1}{(\eta+1)^{1/(p-1)} - 1}\right)^p - 1 - \frac{\eta+1}{((\eta+1)^{1/(p-1)} - 1)^p} \\ &= \left(\frac{(\eta+1)^{1/(p-1)}}{(\eta+1)^{1/(p-1)} - 1}\right)^p - 1 - \frac{\eta+1}{((\eta+1)^{1/(p-1)} - 1)^p} \\ &= \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} - 1. \end{aligned}$$

Summarizing, we have proved the following lemma.

Lemma 2. For all $X, Y \geq 0$ and all $\eta > 0$, it holds

$$(X + Y)^p \leq (1 + \eta)X^p + \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} Y^p.$$

(One easily checks that, in the case $p = 2$,

$$f(\eta) = \frac{(\eta+1)^2 - (\eta+1)}{((\eta+1) - 1)^2} - 1 = \frac{\eta^2 + \eta}{\eta^2} - 1 = \frac{1}{\eta}$$

so that the inequality in Lemma 2 coincides with (5).)

Next we prove (4). Pick p -Legendre conjugate, optimal Kantorovich potentials for $\mathcal{W}_p(\lambda, \nu)$, denoted by α and γ as in the preceding section. Thus

$$\alpha(x) = \inf_{z \in \mathcal{E}} (d(x, z)^p - \gamma(z)), \quad \gamma(z) = \inf_{x \in \mathcal{E}} (d(x, z)^p - \alpha(x));$$

besides $\alpha \in L^1(\mathcal{E}, \lambda)$ while $\gamma \in L^1(\mathcal{E}, \nu)$, and

$$\mathcal{W}_p(\lambda, \nu)^p = \int_{\mathcal{E}} \alpha(x) \lambda(dx) + \int_{\mathcal{E}} \gamma(z) \nu(dz).$$

For each $\eta > 0$, set

$$(6) \quad \beta_\eta(y) := \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} \inf_{z \in \mathcal{E}} \left(d(y, z)^p - \frac{((\eta+1)^{1/(p-1)} - 1)^p}{(\eta+1)^{p/(p-1)} - (\eta+1)} \gamma(z) \right).$$

Obviously, the function

$$y \mapsto \frac{((\eta+1)^{1/(p-1)} - 1)^p}{(\eta+1)^{p/(p-1)} - (\eta+1)} \beta_\eta(y)$$

is d^p -concave, since $\gamma \in L^1(\mathcal{E}, \nu)$ is ν -a.e. finite.

Lemma 3. Under the assumptions above, it holds

$$\alpha(x) - \beta_\eta(y) \leq (1 + \eta)d(x, y)^p, \quad x, y \in \mathcal{E}.$$

Proof of Lemma 3. For each $\epsilon > 0$, there exists $z_\epsilon \in \mathcal{E}$ such that

$$\begin{aligned} & \inf_{z \in \mathcal{E}} \left(\frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} d(y, z)^p - \gamma(z) \right) \\ & \leq \left(\frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} d(y, z_\epsilon)^p - \gamma(z_\epsilon) \right) \\ & < \inf_{z \in \mathcal{E}} \left(\frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} d(y, z)^p - \gamma(z) \right) + \epsilon \end{aligned}$$

Thus

$$\begin{aligned}
\alpha(x) - \beta_\eta(y) &= \inf_{z \in \mathcal{E}} (d(x, z)^p - \gamma(z)) - \inf_{z \in \mathcal{E}} \left(\frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} d(y, z)^p - \gamma(z) \right) \\
&< (d(x, z_\epsilon)^p - \gamma(z_\epsilon)) - \left(\frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} d(y, z_\epsilon)^p - \gamma(z_\epsilon) \right) + \epsilon \\
&\leq (d(x, y) + d(y, z_\epsilon))^p - \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} d(y, z_\epsilon)^p + \epsilon \\
&\leq (1 + \eta) d(x, y)^p + \epsilon
\end{aligned}$$

by Lemma 2. We conclude by letting $\epsilon \rightarrow 0^+$. \square

Assume that $\mathcal{W}_p(\lambda, \mu)\mathcal{W}_p(\mu, \nu) \neq 0$. First observe that

$$|\beta_\eta(y)| \leq \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} (d(x_0, y) + d(x_0, z))^p + |\gamma(z)|,$$

and integrating both sides of this inequality with the measure $\mu \otimes \nu$ shows that

$$\begin{aligned}
\int_{\mathcal{E}} |\beta_\eta(y)| \mu(dy) &\leq 2^{p-1} \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} \left(\int_{\mathcal{E}} d(x_0, y)^p \mu(dy) + \int_{\mathcal{E}} d(x_0, z)^p \nu(dy) \right) \\
&\quad + \int_{\mathcal{E}} |\gamma(z)| \nu(dz) < +\infty,
\end{aligned}$$

since $\mu, \nu \in \mathcal{P}_p(\mathcal{E})$ and $\gamma \in L^1(\mathcal{E}, \nu)$. Hence $\beta_\eta \in L^1(\mathcal{E}, \mu)$ and the inequality in Lemma 3 implies that

$$\int_{\mathcal{E}} \alpha(x) \lambda(dx) - \int_{\mathcal{E}} \beta_\eta(y) \mu(dy) \leq (1 + \eta) \mathcal{W}_p(\lambda, \mu)^p$$

by Kantorovich duality. On the other hand, the definition (6) implies that

$$\beta_\eta(y) + \gamma(z) \leq \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} d(y, z)^p, \quad y, z \in \mathcal{E},$$

so that

$$\int_{\mathcal{E}} \beta_\eta(y) \mu(dy) + \int_{\mathcal{E}} \gamma(z) \nu(dz) \leq \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} \mathcal{W}_p(\mu, \nu)^p$$

again by Kantorovich duality. Hence

$$\begin{aligned}
(7) \quad \mathcal{W}_p(\lambda, \nu)^p &= \int_{\mathcal{E}} \alpha(x) \lambda(dx) + \int_{\mathcal{E}} \gamma(z) \nu(dz) \\
&\leq (1 + \eta) \mathcal{W}_p(\lambda, \mu)^p + \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} \mathcal{W}_p(\mu, \nu)^p,
\end{aligned}$$

and this inequality holds for each $\eta > 0$. Choose

$$\eta + 1 := (Z^{-1/p} + 1)^{p-1}, \quad \text{with} \quad Z := \mathcal{W}_p(\lambda, \mu)^p / \mathcal{W}_p(\mu, \nu)^p.$$

Then

$$\begin{aligned}
(1 + \eta)Z + \frac{(\eta+1)^{p/(p-1)} - (\eta+1)}{((\eta+1)^{1/(p-1)} - 1)^p} &= (Z^{-1/p} + 1)^{p-1} Z + \frac{(Z^{-1/p} + 1)^p - (Z^{-1/p} + 1)^{p-1}}{(Z^{-1/p} + 1 - 1)^p} \\
&= (1 + Z^{1/p})^{p-1} Z^{1/p} + \frac{(Z^{-1/p} + 1 - 1)(Z^{-1/p} + 1)^{p-1}}{(Z^{-1/p} + 1 - 1)^p} \\
&= (1 + Z^{1/p})^{p-1} Z^{1/p} + \frac{Z^{-1/p} (Z^{-1/p} + 1)^{p-1}}{Z^{-1}} \\
&= (1 + Z^{1/p})^{p-1} Z^{1/p} + Z^{(p-1)/p} (Z^{-1/p} + 1)^{p-1} \\
&= (1 + Z^{1/p})^{p-1} Z^{1/p} + (1 + Z^{1/p})^{p-1} \\
&= (1 + Z^{1/p})^p.
\end{aligned}$$

In other words, with this choice of η and Z , one finds that

$$(1 + \eta) \frac{\mathcal{W}_p(\lambda, \mu)^p}{\mathcal{W}_p(\mu, \nu)^p} + \frac{(\eta + 1)^{p/(p-1)} - (\eta + 1)}{((\eta + 1)^{1/(p-1)} - 1)^p} = \left(1 + \frac{\mathcal{W}_p(\lambda, \mu)}{\mathcal{W}_p(\mu, \nu)}\right)^p.$$

Multiplying both sides of this identity by $\mathcal{W}_p(\mu, \nu)^p$, one arrives at the identity

$$(1 + \eta) \mathcal{W}_p(\lambda, \mu)^p + \frac{(\eta + 1)^{p/(p-1)} - (\eta + 1)}{((\eta + 1)^{1/(p-1)} - 1)^p} \mathcal{W}_p(\mu, \nu)^p = (\mathcal{W}_p(\lambda, \mu) + \mathcal{W}_p(\mu, \nu))^p$$

where η is chosen as follows:

$$\eta := \left(\frac{\mathcal{W}_p(\mu, \nu)}{\mathcal{W}_p(\lambda, \mu)} + 1\right)^{p-1} - 1.$$

Inserting this value of η in the right-hand side of (7) and using the identity above shows that

$$\mathcal{W}_p(\lambda, \nu)^p \leq (\mathcal{W}_p(\lambda, \mu) + \mathcal{W}_p(\mu, \nu))^p$$

from which the triangle inequality immediately follows in the special case where

$$\mathcal{W}_p(\lambda, \mu) \mathcal{W}_p(\mu, \nu) \neq 0.$$

Otherwise, if one of the distances $\mathcal{W}_p(\lambda, \mu)$ or $\mathcal{W}_p(\mu, \nu)$ is equal to 0, the triangle inequality is trivial.

5. CONCLUSION

The proof of the triangle inequality for the Wasserstein distances presented in this short note is (perhaps) the most “elementary” proof — which does not mean that it is the shortest — in the sense that it does not use any information about optimal couplings. (For instance, it does not use the existence of an optimal transport map, as in the Brenier theorem, i.e. Theorem 2.12 (ii) in [12].) Also, it does not involve any nontrivial manipulation on optimal couplings (as in the “glueing” procedure described in Lemma 7.6 of [12]). The only ingredients in this proof are (a) Kantorovich duality, and (b) the inequality of Lemma 2, which boils down to computing the Legendre transform of a real-valued function on the half-line. The proof of Lemma 3 is based on (b) — just as Lemma 1 is based on the elementary inequality $2ab \leq \eta a^2 + \frac{1}{\eta} b^2$ for all $a, b, \eta > 0$ — and on the characterization of the infimum of a function as its larger lower bound. Since there is a Kantorovich-type duality for the quantum analogue of \mathcal{W}_2 defined in [4] (see [3]), it seems that the validity of the triangle inequality for this quantum Wasserstein (pseudo)metric boils down to the existence of a quantum analogue of Lemma 1. Since D. Serre’s example mentioned in the introduction rules out the possibility of proving the triangle inequality for the quantum analogue of \mathcal{W}_2 defined in [4] by glueing quantum couplings as explained on p. 28 of [5], we hope that the approach to the triangle inequality presented here can shed light on the quantum case.

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