

A NEW SURVEY: CONE METRIC SPACES

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ABSTRACT. The purpose of this new survey paper is, among other things, to collect in one place most of the articles on cone (abstract, K -metric) spaces, published after 2007. This list can be useful to young researchers trying to work in this part of functional and nonlinear analysis. On the other hand, the existing review papers on cone metric spaces are updated.

The main contribution is the observation that it is usually redundant to treat the case when the underlying cone is solid and non-normal. Namely, using simple properties of cones and Minkowski functionals, it is shown that the problems can be usually reduced to the case when the cone is normal, even with the respective norm being monotone. Thus, we offer a synthesis of the respective fixed point problems arriving at the conclusion that they can be reduced to their standard metric counterparts. However, this does not mean that the whole theory of cone metric spaces is redundant, since some of the problems remain which cannot be treated in this way, which is also shown in the present article.

1. Introduction

Since 1922, when S. Banach proved in his PhD thesis (see [62]) the celebrated Contraction Principle for self-mappings on a complete metric space, several hundreds of researchers have tried to generalize or improve it. Basically, these generalizations were done in two directions—either the contractive condition was replaced by some more general one, or the environment of metric spaces was widened. In the first direction, a lot of improved results appeared, like Kannan's, Chatterjea's, Zamfirescu's, Hardy-Rogers's, Ćirić's, Meir-Keeler's, Boyd-Wong's, to mention just

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a few. The other direction of investigations included introduction of semimetric, quasimetric, symmetric, partial metric, b -metric, and many other classes of spaces.

Of course, not all of these attempts were useful in applications, which should be the main motive for such investigations. Some of them were even not real generalizations, since the obtained results appeared to be equivalent to the already known ones.

It seems that Đ. Kurepa was the first to replace the set \mathbb{R} of real numbers by an arbitrary partially ordered set as a codomain of a metric (see [218]). This approach was used by several authors in mid-20th century, who used various names (abstract metric spaces, K -metric spaces, ...) for spaces thus obtained (see, e.g., [199, 210, 345, 363]). The applications were mostly in numerical analysis.

The interest in such spaces increased after the 2007 paper [153] of L. G. Huang and X. Zhang, who re-introduced the mentioned type of spaces under the name of *cone metric spaces*. Their approach included the use of interior points of the cone which defined the partial order of the space. The original paper [153] used also the assumption of normality of the cone, but later most of the results were obtained for non-normal cones, however with more complicated proofs.

It was spotted very early that (topological vector) cone metric spaces were metrizable (see, e.g., [114, 136, 190, 204]). However, this does not necessarily mean that all fixed point results in cone metric spaces reduce to their standard metric counterparts, since at least some of them still depend on the particular cone that is used. Hence, the research in these spaces has continued and more than 300 papers has appeared—most of them are cited in the list of references of the present paper (we probably skipped some of them, but it was not on purpose).

The intention of this article is, first, to recollect the basic properties of cones in (topological) vector spaces which are important for research in cone metric spaces. In particular (non)-normal and (non)-solid cones are investigated in some details. Then, it is shown that each solid cone in a topological vector space can be essentially replaced by a solid and normal cone in a normed space (even with normal constant equal to 1). Thus, most of the theory of (TVS) cone metric spaces can be easily reduced to the respective problems in standard metric spaces.

It has to be noted that some problems still remain to which the previous assertion cannot be applied—we will mention some of them in Section 4.

The present paper can also be treated as a continuation and refinement of the existing survey articles on this theme, like [170, 201, 273].

2. Topological and ordered vector spaces

We start our paper with some basic facts about ordered topological vector spaces. For more details, the reader may consult any book on this topic, e.g., [25, 101, 182, 314, 357].

2.1. Topological vector spaces. Throughout the paper, E will denote a vector space over the field \mathbb{R} of real numbers, with zero-vector denoted by θ . A topology τ on E is called a *vector topology* if linear operations $(x, y) \mapsto x + y$ and $(\lambda, x) \mapsto \lambda x$ are continuous on $E \times E$, resp. $\mathbb{R} \times E$. In this case, (E, τ) is called a (*real*) *topological vector space* (TVS). If a TVS has a base of neighbourhoods of θ whose elements are (closed and absolutely) convex sets in E , then it is called *locally convex* (LCS).

The topology of an LCS can be characterized using seminorms. Namely, a nonnegative real function p on a vector space E is called a *seminorm* if: 1° $p(x+y) \leq p(x) + p(y)$ for $x, y \in E$; 2° $p(\lambda x) = |\lambda|p(x)$ for $x \in E, \lambda \in \mathbb{R}$. It is easy to prove that a function $p : E \rightarrow \mathbb{R}$ is a seminorm if and only if p is the *Minkowski functional* of an absolutely convex and absorbing set $M \subset E$, i.e., $p = p_M$ is given by

$$x \mapsto p_M(x) = \inf\{\lambda > 0 \mid x \in \lambda M\}.$$

Here, one can take $M = \{x \in E \mid p(x) < 1\}$. The following proposition provides the mentioned characterization.

PROPOSITION 2.1. Let $\{p_i \mid i \in I\}$ be an arbitrary family of seminorms on a vector space E . If $U_i = \{x \in E \mid p_i(x) < 1\}, i \in I$, then the family of all scalar multiples $\lambda U, \lambda > 0$, where U runs through finite intersections $U = \bigcap_{j=1}^n U_j$, forms a base of the neighbourhoods of θ for a locally convex topology τ on E in which all the seminorms p_i are continuous. Each LCS (E, τ) can be described in such a way. If we put in the previous construction $U_i = \{x \in E \mid p_i(x) \leq 1\}$, we obtain a base of neighbourhoods of θ constituted of closed absolutely convex sets.

The easiest (and well known) examples of locally convex spaces are normed and, in particular, Banach spaces. The topology is then generated by a single norm which is the Minkowski functional of the unit ball.

2.2. Cones in ordered topological vector spaces. Let (E, τ) be a real TVS. A subset C of E is called a *cone* if: 1° C is closed, nonempty and $C \neq \{\theta\}$; 2° $x, y \in C$ and $\lambda, \mu \geq 0$ imply that $\lambda x + \mu y \in C$; 3° $C \cap (-C) = \{\theta\}$. Obviously, each cone generates a partial order \preceq_C in E by

$$x \preceq_C y \iff y - x \in C$$

(we will write just \preceq if it is obvious which is the respective cone). And conversely, a partial order \preceq on E generates a cone $C = \{x \in E \mid x \succeq \theta\}$. If \preceq is a partial order on a TVS E , then (E, τ, \preceq) is called an *ordered topological vector space* (OTVS). If $x \preceq y$ and $x \neq y$, we will write $x \prec y$.

The most important examples of OTVS's are special cases of the following one.

EXAMPLE 2.1. Let X be a nonempty set and E be the set of all real-valued functions f defined on X . Let a relation \preceq be defined on E by $f \preceq g$ if and only if $f(x) \leq g(x)$ for all $x \in X$. If τ is a vector topology on E such that the respective cone $C = \{f \in E \mid f(x) \geq 0, x \in X\}$ is τ -closed, then (E, τ, \preceq) is an OTVS.

If (E, \preceq) is an ordered vector space (with the respective cone C) and $x, y \in E$, $x \preceq y$, then the set

$$[x, y] = \{z \in E \mid x \preceq z \preceq y\} = (x + C) \cap (y - C)$$

is called an *order-interval*. A subset A of E is *order-bounded* if it is contained in some order-interval. It is *order-convex* if $[x, y] \subset A$ whenever $x, y \in A$ and $x \preceq y$. It has to be remarked that the families of *convex* and *order-convex* subsets of an ordered vector space are incomparable in general.

An OTVS (E, τ, \preceq) is said to be *order-convex* if it has a base of neighborhoods of θ consisting of order-convex subsets. In this case the order cone C is said to be *normal*. In the case of a normed space, this condition means that the unit ball is order-convex, which is equivalent to the condition that there is a number K such that $x, y \in E$ and $\theta \preceq x \preceq y$ imply that $\|x\| \leq K\|y\|$. The smallest constant K satisfying the last inequality is called the *normal constant* of C .

Equivalently, the cone C in $(E, \|\cdot\|, \preceq_C)$ is normal if the Sandwich Theorem holds, i.e., if

$$(2.1) \quad (\forall n) x_n \preceq y_n \preceq z_n \text{ and } \lim_{n \rightarrow \infty} x_n = \lim_{n \rightarrow \infty} z_n = x \text{ imply } \lim_{n \rightarrow \infty} y_n = x.$$

In particular, if a cone is normal with the constant equal to 1, i.e., if $\theta \preceq x \preceq y$ implies that $\|x\| \leq \|y\|$, the cone is called *monotone* w.r.t. the given norm.

The following is an example of a non-normal cone.

EXAMPLE 2.2. [345] Let $E = C_{\mathbb{R}}^1[0, 1]$ with $\|x\| = \|x\|_{\infty} + \|x'\|_{\infty}$ and $C = \{x \in E \mid x(t) \geq 0, t \in [0, 1]\}$. Consider, for example, $x_n(t) = \frac{t^n}{n}$ and $y_n(t) = \frac{1}{n}$, $n \in \mathbb{N}$. Then $\theta \preceq x_n \preceq y_n$, and $\lim_{n \rightarrow \infty} y_n = \theta$, but $\|x_n\| = \max_{t \in [0, 1]} |\frac{t^n}{n}| + \max_{t \in [0, 1]} |t^{n-1}| = \frac{1}{n} + 1 > 1$; hence $\{x_n\}$ does not converge to zero. It follows by (2.1) that C is a non-normal cone.

The cone C in an OTVS (E, τ) is called *solid* if it has a nonempty interior $\text{int } C$.

There are numerous examples of cones which are solid and normal. Perhaps the easiest is the following one.

EXAMPLE 2.3. Let $E = \mathbb{R}^n$ with the Euclidean topology τ . Let the cone C be given as in Example 2.1, i.e., $C = \{(x_i)_{i=1}^n \mid x_i \geq 0, i = 1, 2, \dots, n\}$. Then it is easy to see that C is a solid and normal cone in (E, τ) .

Example 2.2 shows that there exists a cone which is solid and non-normal. A lot of spaces which are important in functional analysis have cones which are normal and non-solid. We present just two of them.

EXAMPLE 2.4. (see, e.g., [176]) Consider $E = c_0$ (the standard Banach space of all real 0-sequences) and let $C = \{x = \{x_n\} \mid x_n \geq 0, n \in \mathbb{N}\}$. It follows easily that C is a normal cone in E . Let us prove that it has an empty interior.

Take any $x = \{x_n\} \in C$. If $x_n = 0$ for $n \geq n_0$, then obviously $x \notin \text{int } C$. Otherwise, for arbitrary $\varepsilon > 0$, there exists $n_0 \in \mathbb{N}$ such that $x_n < \frac{\varepsilon}{2}$ for all $n > n_0$. Construct a sequence $y = \{y_n\}$ by

$$y_n = \begin{cases} x_n, & \text{if } n \leq n_0, \\ -x_n, & \text{for } n > n_0. \end{cases}$$

Then, at least one of y_n is strictly negative, hence $y \notin C$. However, $\|x - y\| = \sup_{n > n_0} |2x_n| < \varepsilon$, therefore, the ball $B(x, \varepsilon)$ is not a subset of C . Thus, $\text{int } C = \emptyset$.

EXAMPLE 2.5. [242] Let $E = L^2(\mathbb{R}, \mu) \cap C(\mathbb{R})$ be equipped with the norm $\|\cdot\|_E = \|\cdot\|_{L^2} + \|\cdot\|_\infty$, where μ is the Lebesgue measure. Let

$$C = \{h \in E \mid h(t) \geq 0, t \in \mathbb{R}\}$$

be the cone of all positive elements in E . We will show that C has an empty interior. For any $f \in C$ and each $\delta > 0$, define $N_f(\delta) = \{t \in \mathbb{R} \mid f(t) \geq \delta\}$. Then $\mu(N_f(\delta)) < \infty$, and therefore $\mu(\mathbb{R} \setminus N_f(\delta)) = \infty$. Note that

$$\begin{aligned} \mu(\mathbb{R} \setminus N_f(\delta)) &= \mu\left(\bigcup_{r \in \mathbb{Q}} (B(r, \delta) \cap (\mathbb{R} \setminus N_f(\delta)))\right) \\ &\leq \sum_{r \in \mathbb{Q}} \mu(B(r, \delta) \cap (\mathbb{R} \setminus N_f(\delta))) = \infty, \end{aligned}$$

which means that $\mu(A) > 0$, where $A = B(s, \delta) \cap (\mathbb{R} \setminus N_f(\delta))$, for some $s \in \mathbb{Q}$. Define

$$g(x) = \begin{cases} f(x), & x \notin A, \\ f(x) - \delta, & x \in A. \end{cases}$$

Then g is negative on the set A of positive measure and

$$\|f - g\|_{L_2} + \|f - g\|_\infty = \left(\int_A \delta^2 d\mu\right)^{1/2} + \sup_A \delta \leq (2\delta^3)^{1/2} + \delta.$$

Hence, for any $f \in C$ and arbitrary $\varepsilon > 0$, we can find $g \notin C$ with $\|f - g\|_E < \varepsilon$, i.e., there is no ball with centre f that lies inside C . Therefore, C has an empty interior.

We state now the following properties of solid cones.

- [357, Proposition (2.2), page 20] $e \in \text{int } C$ if and only if $[-e, e] = (C - e) \cap (e - C)$ is a τ -neighbourhood of θ .

- If $e \in \text{int } C$, then the Minkowski functional $\|\cdot\|_e = p_{[-e, e]}$ is a norm on the vector space E . Indeed, one has just to prove that $\|x\|_e = 0$ implies that $x = \theta$. Suppose, to the contrary, that $x \neq \theta$. Then, by the definition of infimum, it follows that there is a sequence $\{\lambda_n\}$ of positive reals tending to 0, and such that $x \in \lambda_n[-e, e]$, i.e., $-\lambda_n e \preceq x \preceq \lambda_n e$. It follows that the sequences $\{\lambda_n e - x\}$ and $\{x + \lambda_n e\}$ both belong to C . Since they converge to $-x$ and x , respectively, the closedness of the cone C implies that $-x, x \in C$. Hence, $x = \theta$, which is a contradiction. See also [25, 167].

Note that this conclusion was stated in [200] [the paragraph before Theorem 3.1] under the additional assumption that the cone C is normal. The previous proof shows that this assumption is in fact redundant.

- If $e_1, e_2 \in \text{int } C$, then the respective norms $\|\cdot\|_{e_1}$ and $\|\cdot\|_{e_2}$ are equivalent. In particular, the interiors of the cone C w.r.t. the norms $\|\cdot\|_{e_1}$ and $\|\cdot\|_{e_2}$ coincide; in fact, they are equal to $\text{int}_\tau C$. This follows by the characterization of interior points of a cone in an OTVS.

- If $\text{int}_\tau C \neq \emptyset$, then the topology τ is Hausdorff. Indeed, if $e \in \text{int } C$, then the unit ball $[-e, e]$ is a neighbourhood of θ in the topology generated by the norm $\|\cdot\|_e$. Since this norm topology is Hausdorff and not stronger than τ , it follows that τ is Hausdorff, too.

We will show now that C is a cone, i.e., it is closed, in the topology generated by $\|\cdot\|_e$. Let $x_n \in C$ and $x_n \rightarrow x$ as $n \rightarrow \infty$, in the norm $\|\cdot\|_e$. This means that $-x \preceq -(x - x_n) \preceq \frac{1}{n}e$ for $n \geq n_0$. Passing to the limit as $n \rightarrow \infty$, we get that $-x \preceq \theta$, i.e., $x \succeq \theta$, and so $x \in C$.

Thus, we have proved the next assertion (see also [22, 101, 180, 284, 285, 346]).

PROPOSITION 2.2. If C is a solid cone in an OTVS (E, τ, \preceq_C) , then there exists a norm $\|\cdot\|_e$ on E which is monotone and such that the cone C is normal and solid w.r.t. this norm. In particular, the cone C has the same set of interior points, both in topology τ and in the norm generated by $\|\cdot\|_e$.

Further, following [153], denote

$$(2.2) \quad x \ll y \quad \text{if and only if} \quad y - x \in \text{int } C.$$

Let $\{x_n\}$ be a sequence in (E, τ, \preceq_C) and $c \in \text{int } C$. We will say that $\{x_n\}$ is a *c-sequence* if there exists $n_0 \in \mathbb{N}$ such that $x_n \ll c$ whenever $n \geq n_0$. The connection between *c*-sequences and sequences tending to θ is the following.

- If $x_n \rightarrow \theta$ as $n \rightarrow \infty$, then it is a *c*-sequence for each $c \in \text{int } C$. Indeed, if $c \in \text{int } C$, then $[-c, c]$ is a τ -neighbourhood of θ and it follows that $\text{int}[-c, c] = (\text{int } C - c) \cap (c - \text{int } C)$ is also a τ -neighbourhood of θ . Hence, there exists $n_0 \in \mathbb{N}$ such that, for all $n \geq n_0$, $x_n \in (\text{int } C - c) \cap (c - \text{int } C)$, i.e., $c - x_n \in \text{int } C$, and so $x_n \ll c$.

- The converse of the previous assertion is not true, i.e., $x_n \ll c$ for some $c \in \text{int } C$ and all $n \geq n_0$ does not necessarily imply that $x_n \rightarrow \theta$ (see Example 2.2). However, if the cone C is normal, then these two properties of a sequence $\{x_n\}$ are equivalent.

Note also the following properties of bounded sets.

- If the cone C is solid, then each topologically bounded subset of (E, τ, \preceq_C) is also order-bounded, i.e., it is contained in a set of the form $[-c, c]$ for some $c \in \text{int } C$.

- If the cone C is normal, then each order-bounded subset of (E, τ, \preceq_C) is topologically bounded. Hence, if the cone is both solid and normal, these two properties of subsets of E coincide.

In other words, we have the following property (see, e.g., [345]).

PROPOSITION 2.3. If the underlying cone of an OTVS is solid and normal, then such TVS must be an ordered normed space.

The following old result of M. Krein can also be useful when dealing with cones in normed spaces.

PROPOSITION 2.4. [211] A cone C in a normed space $(E, \|\cdot\|)$ is normal if and only if there exists a norm $\|\cdot\|_1$ on E , equivalent to the given norm $\|\cdot\|$, such that the cone C is monotone w.r.t. $\|\cdot\|_1$.

3. Cone metric spaces

3.1. Definitions and basic properties. As was already said in Introduction, spaces with “metrics” having values in ordered spaces, more general than the set \mathbb{R} of real numbers, appeared under various names (abstract metric spaces, K -metric spaces, ...) since the mid-20th century (see, e.g., [199, 210, 218, 345, 363]). Starting from 2007 and the paper [153], some version of the following definition has been usually used.

DEFINITION 3.1. Let X be a non-empty set and (E, τ, \preceq) be an OTVS. If a mapping $d : X \times X \rightarrow E$ satisfies the conditions

- (i) $d(x, y) \succeq \theta$ for all $x, y \in X$ and $d(x, y) = \theta$ if and only if $x = y$;
- (ii) $d(x, y) = d(y, x)$ for all $x, y \in X$;
- (iii) $d(x, z) \preceq d(x, y) + d(y, z)$ for all $x, y, z \in X$,

then d is called a *cone metric* on X and (X, d) is called a *cone metric space*.

Convergent and Cauchy sequences can be introduced in the following way.

DEFINITION 3.2. Let (X, d) be a cone metric spaces with the cone metric having values in (E, τ, \preceq) , where the underlying cone C is solid. Let $\{x_n\}$ be a sequence in X . Then we say that:

- (1) the sequence $\{x_n\}$ converges to $x \in X$ if for each $c \in \text{int } C$ there exists $n_0 \in \mathbb{N}$ such that $d(x_n, x) \ll c$ holds for all $n \geq n_0$;
- (2) $\{x_n\}$ is a Cauchy sequence if for each $c \in \text{int } C$ there exists $n_0 \in \mathbb{N}$ such that $d(x_m, x_n) \ll c$ holds for all $m, n \geq n_0$;
- (3) the space (X, d) is complete if each Cauchy sequence $\{x_n\}$ in it converges to some $x \in X$.

Note that, according to [180], in the previous definition, equivalent notions are obtained if one replace \ll by \prec or \preceq .

The following crucial observation (which is a consequence of Proposition 2.2) shows that most of the problems in cone metric spaces can be reduced to their standard metric counterparts.

PROPOSITION 3.1. Let X be a non-empty set and (E, τ, \preceq_C) be an OTVS with a solid cone C . If $e \in \text{int } C$ is arbitrary, then $D(x, y) = \|d(x, y)\|_e$ is a (standard) metric on X . Moreover, a sequence $\{x_n\}$ is Cauchy (convergent) in (X, d) if and only if it is Cauchy (convergent) in (X, D) .

We will show in Section 4 how this approach simplifies most of the proofs concerning fixed points of mappings.

Note that it is clear that the cone metric with values in $(E, \|\cdot\|_e, \preceq)$ is continuous (as a function of two variables). Also, Sandwich Theorem holds (since the cone C is normal in the new norm).

3.2. Completion and Cantor's intersection theorem. Most of standard notions from the setting of metric spaces, like accumulation points of sequences, open and closed balls, open and closed subsets, etc., are introduced in the usual way. Also, standard properties (e.g., that closed balls are closed subsets) can be easily deduced, based on Proposition 2.2.

As a sample, we state the following theorem on the completion of a cone metric space and we note that, with the mentioned approach, its proof is much easier than in [11].

THEOREM 3.1. Let (X, d) be a cone metric space over an OTVS (E, τ, \preceq_C) with a solid cone. Then there exists a complete cone metric space (\tilde{X}, \tilde{d}) over an ordered normed space $(E, \|\cdot\|, \preceq_C)$ with a solid and normal cone, containing a dense subset $(\tilde{X}^*, \tilde{d}^*)$, isometric with (X, d) .

Now, we present a proof of the Cantor's intersection theorem in the setting of cone metric spaces.

THEOREM 3.2. Let (X, d) be a cone metric space over an OTVS (E, τ, \preceq_C) with a solid cone. Then (X, d) is complete if and only if every decreasing sequence $\{B_n\}$ of non-empty closed balls in X for which the sequence of diameters tends to θ as $n \rightarrow \infty$, has a non-empty intersection, and more precisely, there exists a point $x \in X$ such that $\bigcap_{n=1}^{\infty} B_n = \{x\}$.

PROOF. According to Propositions 2.2 and 2.4, without loss of generality, we can assume that (X, d) is a cone metric space over an ordered normed space $(E, \|\cdot\|, \preceq_C)$ with the cone C being solid and normal. Moreover, we can assume that the normal constant of C is equal to 1 (i.e., the norm is monotone w.r.t. C).

Assume that (X, d) is a complete cone metric space, and let $B_n = B[x_n, c_n]$, $n \in \mathbb{N}$, be the sequence of non-empty, closed balls in X with the properties: $B_{n+1} \subset B_n$, $n \in \mathbb{N}$, and $c_n \rightarrow \theta$ as $n \rightarrow \infty$. We first show that $\{x_n\}$ is a Cauchy sequence.

If $m > n$, we have $x_m \in B_m \subset B_n$ which implies that $d(x_m, x_n) \preceq c_n$. Since $c_n \rightarrow \theta$ as $n \rightarrow \infty$, it follows that $d(x_m, x_n) \rightarrow \theta$ as $n \rightarrow \infty$, and consequently $\{x_n\}$ is a Cauchy sequence.

The completeness of (X, d) implies the existence of $x \in X$ such that $x_n \rightarrow x$ as $n \rightarrow \infty$. Since $x_m \in B_n$ for all $m > n$, and B_n is a closed subset of X , it follows that $x \in B_n$ for all $n \in \mathbb{N}$, i.e., $x \in \bigcap_{n=1}^{\infty} B_n$.

Suppose that there exists $y \in \bigcap_{n=1}^{\infty} B_n$ such that $y \neq x$. We thus get

$$d(x, y) \preceq d(x, x_n) + d(x_n, y) \preceq 2c_n,$$

which gives $d(x, y) \preceq \theta$ and, as a consequence, we obtain $x = y$, a contradiction. Hence, $\bigcap_{n=1}^{\infty} B_n = \{x\}$.

Conversely, to obtain a contradiction, suppose that (X, d) is not a complete cone metric space. Then there exists a Cauchy sequence $\{x_n\}$ which does not converge in X .

We construct a strictly increasing sequence of positive integers $\{n_i\}$ in the following way. If $c_1 \gg \theta$, then there exists $n_1 \in \mathbb{N}$ such that $m > n_1$ implies $d(x_m, x_{n_1}) \ll c_1$. Now, for $c_2 = \frac{c_1}{2}$ there exists $n_2 > n_1$ such that $d(x_m, x_{n_2}) \ll c_2$ holds for all $m > n_2$. We continue in this manner. For $c_i = \frac{c_{i-1}}{2}$, there exists $n_i > n_{i-1}$ such that $m > n_i$ implies $d(x_m, x_{n_i}) \ll c_i$.

Let us consider the sequence $B_i = B[x_{n_i}, 2c_i]$, $i \in \mathbb{N}$, such that $c_i = \frac{c_1}{2^{i-1}} \rightarrow \theta$ as $i \rightarrow \infty$. We first show that $B_{i+1} \subset B_i$ for all $i \in \mathbb{N}$. From $y \in B_{i+1}$, it follows that $d(y, x_{n_{i+1}}) \preceq 2c_{i+1}$, hence that

$$d(y, x_{n_i}) \preceq d(y, x_{n_{i+1}}) + d(x_{n_{i+1}}, x_{n_i}) \preceq 2c_{i+1} + c_i = 2\frac{c_i}{2} + c_i = 2c_i,$$

and finally that $y \in B[x_{n_i}, 2c_i]$. We thus get $y \in B_i$, which is the desired conclusion.

Let us prove that $\bigcap_{i=1}^{\infty} B_i = \emptyset$. Indeed, if there exists an $x \in \bigcap_{i=1}^{\infty} B_i$, then $x \in B_i$ for all $i \in \mathbb{N}$ and thus $d(x, x_{n_i}) \preceq 2c_i$, $i \in \mathbb{N}$. For $m > n_i$, we have

$$d(x, x_m) \preceq d(x, x_{n_i}) + d(x_{n_i}, x_m) \preceq 2c_i + c_i = 3c_i.$$

The normality of the cone C gives $d(x, x_m) \rightarrow \theta$ as $m \rightarrow \infty$ (since $m > n_i$). This contradicts the fact that the Cauchy sequence $\{x_n\}$ does not converge in X . \square

Comparing the previous proof with the one of [167, Theorem 3.10]), we see that our result is more general and with a shorter proof.

4. Fixed point results in cone metric spaces

4.1. Some fixed point results. Most of the papers from the present list of references dealt with some (common) fixed point problems in cone metric spaces. However, the majority of the obtained results are in fact direct consequences of the corresponding results from the standard metric spaces. We will show this just on certain examples, but it will be clear that the same procedure can be done in most of the other cases.

Thus, let (X, d) be a cone metric space over an OTVS (E, τ, \preceq) with a solid cone C . Let $f, g : X \rightarrow X$ be two self-mappings satisfying $fX \subset gX$, and assume that one of these two subsets of X is complete. Consider the following contractive conditions:

- (1) (Banach) $d(fx, fy) \leq \lambda d(gx, gy)$, $\lambda \in (0, 1)$;
 (2) (Kannan) $d(fx, fy) \leq \lambda d(gx, fx) + \mu d(gy, fy)$, $\lambda, \mu \geq 0$, $\lambda + \mu < 1$;
 (3) (Chatterjea) $d(fx, fy) \leq \lambda d(gx, fy) + \mu d(gy, fx)$, $\lambda, \mu \geq 0$, $\lambda + \mu < 1$;
 (4) (Reich) $d(fx, fy) \leq \lambda d(gx, gy) + \mu d(gx, fx) + \nu d(gy, fy)$, $\lambda, \mu, \nu \geq 0$,
 $\lambda + \mu + \nu < 1$;
 (5) (Zamfirescu) one of the conditions

$$\begin{cases} d(fx, fy) \leq \lambda d(gx, gy), & \lambda \in (0, 1) \\ d(fx, fy) \leq \lambda d(gx, fx) + \mu d(gy, fy), & \lambda, \mu \geq 0, \lambda + \mu < 1 \\ d(fx, fy) \leq \lambda d(gx, fy) + \mu d(gy, fx), & \lambda, \mu \geq 0, \lambda + \mu < 1; \end{cases}$$

- (6) (Hardy-Rogers)

$$d(fx, fy) \leq \lambda d(gx, gy) + \mu d(gx, fx) + \nu d(gy, fy) + \xi d(gx, fy) + \pi d(gy, fx),$$

$$\lambda, \mu, \nu, \xi, \pi \geq 0, \lambda + \mu + \nu + \xi + \pi < 1;$$

- (7) (Ćirić) $d(fx, fy) \leq \lambda u(x, y)$, for some $u(x, y)$ belonging to one of the following sets

$$\begin{cases} \left\{ d(gx, gy), \frac{d(gx, fx) + d(gy, fy)}{2}, \frac{d(gx, fy) + d(gy, fx)}{2} \right\} \\ \left\{ d(gx, gy), d(gx, fx), d(gy, fy), \frac{d(gx, fy) + d(gy, fx)}{2} \right\} \end{cases}$$

where $\lambda \in (0, 1)$.

THEOREM 4.1. If one of the conditions (1)–(7) is satisfied for all $x, y \in X$, then the mappings f and g have a unique point of coincidence. Moreover, if f and g are weakly compatible, then they have a unique common fixed point in X .

PROOF. Let $e \in \text{int } C$ be arbitrary. Based on Propositions 2.2, 2.4 and 3.1, consider the metric space (X, D) , where $D(x, y) = \|d(x, y)\|_e$. Then, the self-mappings $f, g : X \rightarrow X$ satisfy one of the following contractive conditions:

- (1') $D(fx, fy) \leq \lambda D(gx, gy)$, $\lambda \in (0, 1)$;
 (2') $D(fx, fy) \leq \lambda D(gx, fx) + \mu D(gy, fy)$, $\lambda, \mu \geq 0$, $\lambda + \mu < 1$;
 (3') $D(fx, fy) \leq \lambda D(gx, fy) + \mu D(gy, fx)$, $\lambda, \mu \geq 0$, $\lambda + \mu < 1$;
 (4') $D(fx, fy) \leq \lambda D(gx, gy) + \mu D(gx, fx) + \nu D(gy, fy)$, $\lambda, \mu, \nu \geq 0$, $\lambda + \mu + \nu < 1$;
 (5') one of the conditions

$$\begin{cases} D(fx, fy) \leq \lambda D(gx, gy), & \lambda \in (0, 1) \\ D(fx, fy) \leq \lambda D(gx, fx) + \mu D(gy, fy), & \lambda, \mu \geq 0, \lambda + \mu < 1 \\ D(fx, fy) \leq \lambda D(gx, fy) + \mu D(gy, fx), & \lambda, \mu \geq 0, \lambda + \mu < 1; \end{cases}$$

- (6')

$$D(fx, fy) \leq \lambda D(gx, gy) + \mu D(gx, fx) + \nu D(gy, fy) + \xi D(gx, fy) + \pi D(gy, fx),$$

$\lambda, \mu, \nu, \xi, \pi \geq 0, \lambda + \mu + \nu + \xi + \pi < 1;$
 (7') one of the conditions

$$D(fx, fy) \leq \lambda \left\{ D(gx, gy), \frac{D(gx, fx) + D(gy, fy)}{2}, \frac{D(gx, fy) + D(gy, fx)}{2} \right\}$$

$$D(fx, fy) \leq \lambda \left\{ D(gx, gy), D(gx, fx), D(gy, fy), \frac{D(gx, fy) + D(gy, fx)}{2} \right\}$$

where $\lambda \in (0, 1)$.

It is well known (see, e.g., [304] for the case $g = id_X$; the general cases are similar) that, in each of these cases, it follows that the mappings f and g have a unique point of coincidence. The conclusion in the case of weak compatibility is also standard (see, e.g., [177]). \square

For Ćirić's quasicontraction (see also [304]), but for a single mapping, the following cone metric version can be proved in a similar way.

THEOREM 4.2. Let (X, d) be a complete cone metric space over an OTVS (E, τ, \preceq) with a solid cone C . Let $f : X \rightarrow X$ be a self-mapping such that there exists $\lambda \in (0, 1)$ and, for all $x, y \in X$ there exists

$$u(x, y) \in \{d(x, y), d(x, fx), d(y, fy), d(x, fy), d(y, fx)\}$$

satisfying $d(fx, fy) \preceq \lambda u(x, y)$. Then f has a unique fixed point in X .

4.2. Results that cannot be obtained in the mentioned way. Certain fixed point problems in cone metric spaces cannot be treated as in the previous subsection. This is always the case when the given contractive condition cannot be transformed to an appropriate condition in the corresponding metric space (X, D) . As an example of this kind we recall a Boyd-Wong type result.

Let (E, τ, \preceq_C) be an OTVS with a solid cone. A mapping $\varphi : C \rightarrow C$ is called a *comparison function* if: (i) φ is nondecreasing w.r.t. \preceq ; (ii) $\varphi(\theta) = \theta$ and $\theta \prec \varphi(c) \prec c$ for $c \in C \setminus \{\theta\}$; (iii) $c \in \text{int } C$ implies $c - \varphi(c) \in \text{int } C$; (iv) if $c \in C \setminus \{\theta\}$ and $e \in \text{int } C$, then there exists $n_0 \in \mathbb{N}$ such that $\varphi^n(c) \ll e$ for each $n \geq n_0$.

THEOREM 4.3. [31, Theorem 2.1] Let (X, d) be a complete cone metric space over (E, τ, \preceq_C) with a solid cone. Let the mappings $f, g : X \rightarrow X$ be weakly compatible and suppose that for some comparison function $\varphi : C \rightarrow C$ and for all $x, y \in X$ there exists $u \in \{d(gx, gy), d(gx, fx), d(gy, fy)\}$, such that $d(fx, fy) \preceq \varphi(u)$. Then f and g have a unique common fixed point in X .

An additional example is provided by the following result.

THEOREM 4.4. [99] Let (X, d) be a complete cone metric space over $(E, \|\cdot\|, \preceq_C)$ with a solid cone. Let $f : X \rightarrow X$ and suppose that there exists a positive bounded operator on E with the spectral radius $r(A) < 1$, such that $d(fx, fy) \preceq A(d(x, y))$ for all $x, y \in X$. Then f has a unique fixed point in X .

In this case, passing to the space $(E, \|\cdot\|_e, \preceq_C)$ cannot help, since the two norms need not be equivalent and we have no information about the boundedness of A and (if it is bounded) how $r(A)$ has changed.

A very important special class of fixed point results are the Caristi-type ones, and the huge literature is devoted to them. When cone metric spaces are concerned, they are treated in details, e.g., in the papers [19, 85, 193, 200–202, 353], so we will give here only some basic information.

The following result was proved in [19].

THEOREM 4.5. [19, Theorem 2] Let (X, d) be a complete cone metric space over an OTVP $(E, \|\cdot\|, \preceq_C)$ with a solid cone. Let $F : X \rightarrow C$ be a lower-semi-continuous map and let $f : X \rightarrow X$ satisfy the condition

$$d(x, fx) \preceq F(x) - F(f(x))$$

for any $x \in X$. Then f has a fixed point.

It is not clear whether, by passing to the space $(E, \|\cdot\|_e, \preceq)$ using the Minkowski functional, this theorem reduces to the classical Caristi result. However, it is proved in [202] that this is still the case if $e \in \text{int } C$ can be chosen so that the corresponding Minkowski functional $p_{[-e, e]}$ is additive. It is an open question whether this can be done without this assumption.

5. Some “hybrid” spaces

As has been already mentioned, besides cone metric spaces, a lot of other generalizations of standard metric spaces have been introduced and fixed point problems in these settings have been investigated by several authors. There are among them some “hybrid” spaces, i.e., spaces where axioms of several types are used simultaneously. Such are, e.g., cone b -metric spaces, cone- G -metric spaces, cone rectangular metric spaces, partial cone metric spaces, cone spaces with c -distance and some others. We will recall here definitions of two of these classes and how the work in these classes can be easily reduced to the already known ones. Similar conclusions hold for the other mentioned classes, too.

5.1. Cone b -metric spaces. Cone b -metric spaces were introduced (under a different name) in [97] and some fixed point results were presented in this setting.

DEFINITION 5.1. Let X be a non-empty set, (E, τ, \preceq) be an OTVS and $s \geq 1$ be a real number. If a mapping $d : X \times X \rightarrow E$ satisfies the conditions

- (i) $d(x, y) \succeq \theta$ for all $x, y \in X$ and $d(x, y) = \theta$ if and only if $x = y$;
- (ii) $d(x, y) = d(y, x)$ for all $x, y \in X$;
- (iii) $d(x, z) \preceq s(d(x, y) + d(y, z))$ for all $x, y, z \in X$,

then d is called a *cone b -metric* on X and (X, d) is called a *cone b -metric space with parameter s* .

Later, these and other researchers obtained a lot of (common) fixed point results (see, [57, 63, 131, 137, 146, 234, 263, 323, 334, 360, 366]). However, similarly as in the case of cone metric spaces, most of these results can be reduced to the case of classical b -metric spaces of Bakhtin [61] and Czerwik [100]. Namely, similarly as Proposition 3.1, the following can be deduced from Proposition 2.2.

PROPOSITION 5.1. Let X be a non-empty set, (E, τ, \preceq_C) be an OTVS with a solid cone C and $s \geq 1$ be a real number. If $e \in \text{int } C$ is arbitrary, then $D(x, y) = \|d(x, y)\|_e$ is a b -metric on X . Moreover, a sequence $\{x_n\}$ is Cauchy (convergent) in (X, d) if and only if it is Cauchy (convergent) in (X, D) .

5.2. Cone rectangular spaces. The following definition was given in [50].

DEFINITION 5.2. Let X be a non-empty set and (E, τ, \preceq) be an OTVS. If a mapping $d : X \times X \rightarrow E$ satisfies the conditions

- (i) $d(x, y) \succeq \theta$ for all $x, y \in X$ and $d(x, y) = \theta$ if and only if $x = y$;
- (ii) $d(x, y) = d(y, x)$ for all $x, y \in X$;
- (iii) $d(x, y) \preceq d(x, w) + d(w, z) + d(z, y)$ for all $x, y \in X$ and all distinct points $w, z \in X \setminus \{x, y\}$,

then d is called a *cone rectangular metric* on X and (X, d) is called a *cone rectangular metric space*.

In the papers [50, 174, 235, 238, 298, 339, 346], some fixed point results in cone rectangular spaces were obtained. The following proposition shows how most of these results can be easily reduced to the corresponding known ones in the environment of rectangular spaces defined by Branciari in [73].

PROPOSITION 5.2. Let X be a non-empty set and (E, τ, \preceq_C) be an OTVS with a solid cone C . If $e \in \text{int } C$ is arbitrary, then $D(x, y) = \|d(x, y)\|_e$ is a rectangular metric on X . Moreover, a sequence $\{x_n\}$ is Cauchy (convergent) in (X, d) if and only if it is Cauchy (convergent) in (X, D) .

6. The case of a non-solid cone

In this section, we will briefly consider the case when the underlying cone is non-solid, but normal.

Let $(E, \|\cdot\|, \preceq_C)$ be an ordered normed space and let the cone C be normal, but non-solid (see, e.g., Examples 2.4 and 2.5). The definition of a cone metric d on a nonempty set X , over E , is the same as Definition 3.1. However, definition of convergent and Cauchy sequences, as well as of the completeness, must be modified.

DEFINITION 6.1. Let (X, d) be a cone metric space over $(E, \|\cdot\|, \preceq_C)$, with the cone C being normal (possibly non-solid). A sequence $\{x_n\}$ in X is said to converge to $x \in X$ if $d(x_n, x) \rightarrow \theta$ as $n \rightarrow \infty$ (the convergence in the sense of norm in E). Similarly, Cauchy sequences are introduced, as well as the completeness of the space.

In view of Proposition 2.4, we can assume that the normal constant of C is equal to 1, and further consider just the standard metric space (X, D) , where $D(x, y) = \|d(x, y)\|$.

Open (resp. closed) balls in (X, d) can be introduced as follows: let $x \in X$ and $c \in C \setminus \{\theta\}$. The open (resp. closed) ball with centre x and radius c are given by $B(x, c) = \{y \in X \mid d(y, x) \prec c\}$ (resp. $B(x, c) = \{y \in X \mid d(y, x) \preceq c\}$). It can be easily shown that an open (closed) ball is an open (closed) subset of (X, d) . We will show this, e.g., in the case of a closed ball.

Thus, let $y_n \in B[x, c]$ and $y_n \rightarrow y$ as $n \rightarrow \infty$ in (X, d) . Then we have $d(y, x) \preceq d(y, y_n) + d(y_n, x) \preceq d(y, y_n) + c$. By the Sandwich Theorem (which holds since the cone C is normal), we get that $d(y, x) \preceq c$, which means that $y \in B(x, c)$.

However, note that the collection of open balls $\{B(x, c) \mid x \in X, c \in C \setminus \{\theta\}\}$ does not necessarily form a base of topology on X . Indeed, it is not sure that the intersection of two open balls contains a ball. For example, for $X = \mathbb{R}^2$, $C = \{(x, y) \mid x, y \geq 0\}$ and the points $c_1 = (1, 0)$, $c_2 = (0, 1)$ from $C \setminus \{\theta\}$, there is no $c \in C \setminus \{\theta\}$ such that $c \prec c_1$ and $c \prec c_2$.

Nevertheless, the theorem on completion holds in this case, too.

We conclude with the following open question.

QUESTION 6.1. Construct a cone in a real TVS which is both non-normal and non-solid.

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