

# Fixed point theorems for $(F, \psi, \varphi)$ – contractions on ordered S-Complete Hausdorff uniform spaces

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**Abstract:** The aim of this paper is to prove some new fixed point theorems for  $(F, \psi, \varphi)$  – weak contractions on ordered S-complete Hausdorff uniform spaces. Our results extend existing results in the literature.

**Keywords:** Fixed point,  $(F, \psi, \varphi)$ -contraction, C-class function, E-distance, S-complete space.

## 1 Introduction

Aamri and El Moutawakil [2] proved some common fixed point theorems for some new contractive or expansive maps in uniform spaces by introducing the notions of an  $E$ –distance. Some other authors proved fixed point theorems using this concept ([1],[3-5],[8],[10],[11],[18],[19],[22],[23]).

Existence of fixed points in partially ordered metric spaces was first investigated in 2004 by Ran and Reurings [21] and then by Nieto and Lopez [17]. Recently, some results were proved in this direction ([9],[10],[13],[16],[20]).

**Definition 1.** ([2]) Let  $(X, \vartheta)$  be a uniform space. A function  $p : X \times X \rightarrow \mathbb{R}^+$  is said to be an  $A$ –distance if for any  $V \in \vartheta$ , there exists  $\delta > 0$ , such that  $p(z, x) \leq \delta$  and  $p(z, y) \leq \delta$  for some  $z \in X$  imply  $(x, y) \in V$ .

**Definition 2.** ([2]) Let  $(X, \vartheta)$  be a uniform space. A function  $p : X \times X \rightarrow \mathbb{R}^+$  is said to be an  $E$ –distance if

(p1)  $p$  is an  $A$ –distance, (p2)  $p(x, y) \leq p(x, z) + p(z, y)$  for all  $x, y, z \in X$ .

**Example 1.** ([2]) Let  $X = [0, +\infty)$  and  $p(x, y) = \max\{x, y\}$ . The function  $p$  is an  $A$ –distance. Also,  $p$  is an  $E$ –distance.

The following lemma embodies some useful properties of  $E$ –distance.

**Lemma 1.** ([1],[2]) Let  $(X, \vartheta)$  be a Hausdorff uniform space and  $p$  be an  $E$ -distance on  $X$ . Let  $\{x_n\}$  and  $\{y_n\}$  be arbitrary sequences in  $X$  and  $\{\alpha_n\}, \{\beta_n\}$  be sequences in  $\mathbb{R}^+$  converging to 0. Then, for  $x, y, z \in X$ , the following holds

(a) If  $p(x_n, y) \leq \alpha_n$  and  $p(x_n, z) \leq \beta_n$  for all  $n \in \mathbb{N}$ , then  $y = z$ . In particular, if  $p(x, y) = 0$  and  $p(x, z) = 0$ , then  $y = z$ .

(b) If  $p(x_n, y_n) \leq \alpha_n$  and  $p(x_n, z) \leq \beta_n$  for all  $n \in \mathbb{N}$ , then  $\{y_n\}$  converges to  $z$ .

(c) If  $p(x_n, x_m) \leq \alpha_n$  for all  $m > n$ , then  $\{x_n\}$  is a Cauchy sequence in  $(X, \vartheta)$ .

Let  $(X, \vartheta)$  be a uniform space equipped with  $E$ – distance  $p$ . A sequence in  $X$  is  $p$ –Cauchy if it satisfies the usual metric condition. There are several concepts of completeness in this setting.

**Definition 3.** ([1], [2]) Let  $(X, \vartheta)$  be a uniform space and  $p$  be an  $E$ – distance on  $X$ . Then

- (i)  $X$  is said to be  $S$ –complete if for every  $p$ –Cauchy sequence  $\{x_n\}$  there exists  $x \in X$  with  $\lim_{n \rightarrow \infty} p(x_n, x) = 0$ ,
- (ii)  $X$  is said to be  $p$ –Cauchy complete if for every  $p$ –Cauchy sequence  $\{x_n\}$  there exists  $x \in X$  with  $\lim_{n \rightarrow \infty} x_n = x$  with respect to  $\tau(\vartheta)$ ,
- (iii)  $f : X \rightarrow X$  is  $p$ –continuous if  $\lim_{n \rightarrow \infty} p(x_n, x) = 0$  implies  $\lim_{n \rightarrow \infty} p(fx_n, fx) = 0$ ,
- (iv)  $f : X \rightarrow X$  is  $\tau(\vartheta)$ –continuous if  $\lim_{n \rightarrow \infty} x_n = x$  with respect to  $\tau(\vartheta)$  implies  $\lim_{n \rightarrow \infty} fx_n = fx$  with respect to  $\tau(\vartheta)$ .

*Remark.* ([2]) Let  $(X, \vartheta)$  be a Hausdorff uniform space and let  $\{x_n\}$  be a  $p$ –Cauchy sequence. Suppose that  $X$  is  $S$ –complete, then there exists  $x \in X$  such that  $\lim_{n \rightarrow \infty} p(x_n, x) = 0$ . Lemma 4 (b) then gives  $\lim_{n \rightarrow \infty} x_n = x$  with respect to the topology  $\tau(\vartheta)$ . Therefore  $S$ –completeness implies  $p$ –Cauchy completeness.

In 2014, the concept of  $C$ -class functions were introduced by H. Ansari in [6]. After some fixed point theorems were given using this concept ([7],[12],[14]).

**Definition 4.** ([6]) A mapping  $F : [0, \infty)^2 \rightarrow \mathbb{R}$  is called  $C$ -class function if it is continuous and satisfies following axioms.

- (1)  $F(s, t) \leq s$ ;
- (2)  $F(s, t) = s$  implies that either  $s = 0$  or  $t = 0$ ; for all  $s, t \in [0, \infty)$ .

Note for some  $F$  we have that  $F(0, 0) = 0$ . We denote  $C$ -class functions as  $\mathcal{C}$ .

**Example 2.** The following functions  $F : [0, \infty)^2 \rightarrow \mathbb{R}$  are elements of  $\mathcal{C}$ , for all  $s, t \in [0, \infty)$ .

- (1)  $F(s, t) = s - t, F(s, t) = s \Rightarrow t = 0$ ;
- (2)  $F(s, t) = ms, 0 < m < 1, F(s, t) = s \Rightarrow s = 0$ ;
- (3)  $F(s, t) = \frac{s}{(1+t)^r}; r \in (0, \infty), F(s, t) = s \Rightarrow s = 0$  or  $t = 0$ ;
- (4)  $F(s, t) = \log(t + a^s)/(1 + t), a > 1, F(s, t) = s \Rightarrow s = 0$  or  $t = 0$ ;
- (5)  $F(s, t) = \ln(1 + a^s)/2, a > e, F(s, 1) = s \Rightarrow s = 0$ ;
- (6)  $F(s, t) = (s + t)^{1/(1+t)^r} - t, l > 1, r \in (0, \infty), F(s, t) = s \Rightarrow t = 0$ ;
- (7)  $F(s, t) = s \log_{t+a} a, a > 1, F(s, t) = s \Rightarrow s = 0$  or  $t = 0$ ;
- (8)  $F(s, t) = s - \left(\frac{1+s}{2+s}\right)\left(\frac{t}{1+t}\right), F(s, t) = s \Rightarrow t = 0$ ;
- (9)  $F(s, t) = s\beta(s), \beta : [0, \infty) \rightarrow (0, 1)$ , and is continuous,  $F(s, t) = s \Rightarrow s = 0$ ;
- (10)  $F(s, t) = s - \frac{t}{k+t}, F(s, t) = s \Rightarrow t = 0$ ;
- (11)  $F(s, t) = s - \varphi(s), F(s, t) = s \Rightarrow s = 0$ , here  $\varphi : [0, \infty) \rightarrow [0, \infty)$  is a continuous function such that  $\varphi(t) = 0 \Leftrightarrow t = 0$ ;
- (12)  $F(s, t) = sh(s, t), F(s, t) = s \Rightarrow s = 0$ , here  $h : [0, \infty) \times [0, \infty) \rightarrow [0, \infty)$  is a continuous function such that  $h(t, s) < 1$  for all  $t, s > 0$ ;
- (13)  $F(s, t) = s - \left(\frac{2+t}{1+t}\right)t, F(s, t) = s \Rightarrow t = 0$ ;
- (14)  $F(s, t) = \sqrt[n]{\ln(1 + s^n)}, F(s, t) = s \Rightarrow s = 0$ ;
- (15)  $F(s, t) = \phi(s), F(s, t) = s \Rightarrow s = 0$ , here  $\phi : [0, \infty) \rightarrow [0, \infty)$  is an upper semicontinuous function such that  $\phi(0) = 0$ , and  $\phi(t) < t$  for  $t > 0$ ;
- (16)  $F(s, t) = \frac{s}{(1+s)^r}; r \in (0, \infty), F(s, t) = s \Rightarrow s = 0$ .

We shall also state the following definition of altering distance function which is required in the sequel to establish a fixed point theorem in uniform space.

**Definition 5.** ([15]) A function  $\psi : [0, \infty) \rightarrow [0, \infty)$  is called an altering distance function if the following properties are satisfied:

- (i)  $\psi(0) = 0$ ,
- (ii)  $\psi$  is continuous and monotonically nondecreasing.

*Remark.* We denote set of altering distance functions by  $\Psi$ .

In this paper, we assume that

**Definition 6.** ([6]) An ultra altering distance function is a continuous, nondecreasing mapping  $\phi : [0, \infty) \rightarrow [0, \infty)$  such that  $\phi(t) > 0, t > 0$  and  $\phi(0) \geq 0$ .

*Remark.* We denote set ultra altering distance functions by  $\Phi_u$ .

## 2 Fixed point results

In this section, we prove some fixed point results using C-class function in ordered uniform spaces.

**Theorem 1.** Let  $(X, \vartheta, \preceq)$  be an ordered Hausdorff uniform space and  $p$  be an E-distance on S-complete and  $p$ -bounded space  $X$ . Let  $f, g : X \rightarrow X$  be two commuting  $p$ -continuous or  $\tau(\vartheta)$ -continuous selfmappings such that

- (i)  $f(X) \subseteq g(X)$ ,
- (ii)  $f$  is  $g$ -nondecreasing,
- (iii)  $\psi(p(fx, fy)) \leq F(\psi(p(gx, gy)), \phi(p(gx, gy)))$  for all  $x, y \in X$  with  $gx \preceq gy$  where  $\psi \in \Psi, \phi \in \Phi_u$  and  $F \in \mathcal{C}$

If there exists  $x_0 \in X$  with  $gx_0 \preceq fx_0$  then  $f$  and  $g$  have an unique common fixed point.

*Proof.* If  $x_0 \in X$  such that  $gx_0 \preceq fx_0$ . Since  $f(X) \subseteq g(X)$ , we can choose  $x_1 \in X$  such that  $fx_0 = gx_1$ . Then  $gx_0 \preceq fx_0 = gx_1$ . As  $f$  is  $g$ -nondecreasing, we get  $fx_0 \preceq fx_1$ . Continuing this process, we can construct a sequence  $\{x_n\}$  in  $X$  such that

$$gx_n = fx_{n-1}, \quad n = 1, 2, \dots$$

for which

$$gx_0 \preceq fx_0 = gx_1 \preceq fx_1 = gx_2 \preceq \dots \preceq fx_{n-1} = gx_n \preceq \dots$$

From (iii),

$$\begin{aligned} \psi(p(fx_n, fx_{n+1})) &\leq F(\psi(p(gx_n, gx_{n+1})), \phi(p(gx_n, gx_{n+1}))) \\ &\leq \psi(p(gx_n, gx_{n+1})) = \psi(p(fx_{n-1}, fx_n)) \end{aligned} \tag{1}$$

so  $p(fx_n, fx_{n+1}) \leq p(fx_{n-1}, fx_n)$ , therefore  $\{p(fx_n, fx_{n+1})\}$ , is decreasing so tend to  $r \geq 0$ ,

In (1), on taking limit as  $n \rightarrow \infty$ , by definiton of  $F$ ,

$$\psi(r) \leq F(\psi(r), \phi(r)) \leq \psi(r).$$

So,  $\psi(r) = 0$ , or  $\phi(r) = 0$ , therefore  $r = 0$ . Hence

$$\lim_{n \rightarrow \infty} p(x_{n+1}, x_n) = 0.$$

Similarly, we can show

$$\lim_{n \rightarrow \infty} p(x_n, x_{n+1}) = 0.$$

Next we show that  $\{x_n\}$  is a  $p$ -Cauchy sequence. Assume  $\{y_n = fx_n\}$  is not  $p$ -Cauchy. Then there exists an  $\varepsilon > 0$  for which we can find subsequences  $\{y_{m(k)}\}$  and  $\{y_{n(k)}\}$  of  $\{y_n\}$  with  $m(k) > n(k) > k$  such that

$$p(y_{n(k)}, y_{m(k)}) \geq \varepsilon. \quad (2)$$

Further, corresponding to  $n(k)$ , we can choose  $m(k)$  in such a way that it is the smallest integer with  $m(k) > n(k)$  and satisfying (2). Hence,

$$p(y_{n(k)}, y_{m(k)-1}) < \varepsilon.$$

Then we have

$$\varepsilon \leq p(y_{n(k)}, y_{m(k)}) \leq p(y_{n(k)}, y_{m(k)-1}) + p(y_{m(k)-1}, y_{m(k)}),$$

that is

$$\varepsilon \leq p(y_{n(k)}, y_{m(k)}) < \varepsilon + p(y_{m(k)-1}, y_{n(k)}).$$

Taking the limit as  $k \rightarrow \infty$ , we have

$$\lim_{k \rightarrow \infty} p(x_{n(k)}, x_{m(k)}) = \varepsilon. \quad (3)$$

From (p2),

$$p(y_{n(k)}, y_{m(k)}) \leq p(y_{n(k)}, y_{n(k)+1}) + p(y_{n(k)+1}, y_{m(k)+1}) + p(y_{m(k)+1}, y_{m(k)})$$

and

$$p(y_{n(k)+1}, y_{m(k)+1}) \leq p(y_{n(k)+1}, y_{n(k)}) + p(y_{n(k)}, y_{m(k)}) + p(y_{m(k)}, y_{m(k)+1}).$$

Taking the limit as  $k \rightarrow \infty$  we have

$$\lim_{k \rightarrow \infty} p(y_{n(k)+1}, y_{m(k)+1}) = \varepsilon. \quad (4)$$

From (iii),

$$\begin{aligned} \psi(p(y_{n(k)+1}, y_{m(k)+1})) &= \psi(p(fx_{n(k)+1}, fx_{m(k)+1})) \\ &\leq F(\psi(p(gx_{n(k)+1}, gx_{m(k)+1})), \varphi(p(gx_{n(k)+1}, gx_{m(k)+1}))) \\ &= F(\psi(p(fx_{n(k)}, fx_{m(k)})), \varphi(p(fx_{n(k)}, fx_{m(k)}))) \\ &= F(\psi(p(y_{n(k)}, y_{m(k)})), \varphi(p(y_{n(k)}, y_{m(k)}))). \end{aligned}$$

Letting  $k \rightarrow \infty$  in the above inequality, using (3), (4), the continuities of  $\psi$  and  $\varphi$  and definition of  $F$ , we have

$$\psi(\varepsilon) \leq F(\psi(\varepsilon), \varphi(\varepsilon)) \leq \psi(\varepsilon).$$

So,  $\psi(\varepsilon) = 0$  or  $\varphi(\varepsilon) = 0$ , therefore  $\varepsilon = 0$  which is a contradiction. Hence  $\{fx_n\}$  is a  $p$ -Cauchy sequence. Since  $S$ -completeness of  $X$ , there exists a  $z \in X$  such that

$$\lim_{n \rightarrow \infty} p(fx_n, z) = 0 \text{ and } \lim_{n \rightarrow \infty} p(gx_n, z) = 0$$

Moreover, the  $p$ -continuity of  $f$  and  $g$  implies that

$$\lim_{n \rightarrow \infty} p(gfx_n, gz) = \lim_{n \rightarrow \infty} p(fgx_n, fz) = 0.$$

Since  $f$  and  $g$  are commuting, then  $fg = gf$ . So we have

$$\lim_{n \rightarrow \infty} p(fgx_n, gz) = \lim_{n \rightarrow \infty} p(fgx_n, fz) = 0.$$

By Lemma 4(a), we have  $fz = gz$ . Since  $fg = gf$ , we have  $ffz = fgz = gfz = ggz$ . From (iii) and definition of  $F, \psi$  and  $\varphi$ ,

$$\begin{aligned} \psi(p(fz, ffz)) &\leq F(\psi(p(gz, gfz)), \varphi(p(gz, gfz))) \\ &= F(\psi(p(fz, ffz)), \varphi(p(fz, ffz))) \end{aligned} \tag{5}$$

so,  $\psi(p(fz, ffz)) = 0$ , or  $\varphi(p(fz, ffz)) = 0$ . Thus  $p(fz, ffz) = 0$ . Again From (iii), we have

$$\begin{aligned} \psi(p(fz, fz)) &\leq F(\psi(p(gz, gz)), \varphi(p(gz, gz))) \\ &= F(\psi(p(fz, fz)), \varphi(p(fz, fz))) \end{aligned} \tag{6}$$

so,  $\psi(p(fz, fz)) = 0$ , or  $\varphi(p(fz, fz)) = 0$ . Thus  $p(fz, fz) = 0$ . Thus from (5), (6) and Lemma 4(a), we get  $ffz = fz$ . Hence  $fz$  is common fixed point of  $f$  and  $g$ . The proof is similar when  $T$  is  $\tau(\vartheta)$ -continuous.

Now, we show uniqueness. Suppose that there exists  $u, t \in X$  such that  $fu = gu = u$  and  $ft = gt = t$ . Then by (iii),

$$\begin{aligned} \psi(p(u, t)) &= \psi(p(fu, ft)) \leq F(\psi(p(gu, gt)), \varphi(p(gu, gt))) \\ &= F(\psi(p(u, t)), \varphi(p(u, t))) \end{aligned}$$

so,  $\psi(p(u, t)) = 0$ , or  $\varphi(p(u, t)) = 0$ . Thus  $p(u, t) = 0$ . Similarly, we show that  $p(t, u) = 0$ . By (p2)

$$p(u, u) \leq p(u, t) + p(t, u)$$

and therefore  $p(u, u) = 0$ . By Lemma 4 (a), we have  $u = t$ .

**Corollary 1.** Let  $(X, \vartheta, \preceq)$  be an ordered Hausdorff uniform space. Suppose  $p$  be an  $E$ -distance on  $S$ -complete and  $p$ -bounded space  $X$ . Let  $f : X \rightarrow X$  be a  $p$ -continuous or  $\tau(\vartheta)$ -continuous nondecreasing mapping such that for all comparable  $x, y \in X$  with

$$\psi(p(fx, fy)) \leq F(\psi(p(x, y)), \varphi(p(x, y)))$$

where  $\psi \in \Psi$ ,  $\varphi \in \Phi$  and  $F \in \mathcal{C}$ .

If there exists  $x_0 \in X$  with  $x_0 \preceq f(x_0)$  then  $f$  has a fixed point.

**Corollary 2.** ([23]) Let  $(X, \vartheta, \preceq)$  be a Hausdorff uniform space, " $\preceq$ " be a partial order on  $X$  and  $p$  be an  $E$ -distance on  $S$ -complete space  $X$ . Let  $f : X \rightarrow X$  be a  $p$ -continuous or  $\tau(\vartheta)$ -continuous nondecreasing mapping such that for all comparable  $x, y \in X$  with

$$\psi(p(fx, fy)) \leq \psi(p(x, y)) - \varphi(p(x, y))$$

where  $\psi, \varphi : [0, \infty) \rightarrow [0, \infty)$  are altering distance functions.

If there exists  $x_0 \in X$  with  $x_0 \preceq f(x_0)$  then  $f$  has a fixed point.

**Corollary 3.** Let  $(X, \vartheta, \preceq)$  be an ordered Hausdorff uniform space. Suppose  $p$  be an  $E$ -distance on  $S$ -complete and  $p$ -bounded space  $X$ . Let  $f : X \rightarrow X$  be a  $p$ -continuous or  $\tau(\vartheta)$ -continuous nondecreasing mapping such that for all

comparable  $x, y \in X$  with

$$\psi(p(fx, fy)) \leq k\psi(p(x, y))$$

where  $\psi : [0, \infty) \rightarrow [0, \infty)$  is an altering distance function and  $0 < k < 1$ .

If there exists  $x_0 \in X$  with  $x_0 \preceq f(x_0)$  then  $f$  has a fixed point.

**Example 3.** Let  $F(s, t) = \ln(1 + s)$ ,  $X = [0, 1]$  equipped with usual metric  $d(x, y) = |x - y|$  and a partial order be defined as  $x \preceq y$  whenever  $y \leq x$  and suppose

$$\vartheta = \{V \subset X \times X : \Delta \subset V\}.$$

Define the function  $p$  as  $p(x, y) = y$  for all  $x, y$  in  $X$  and  $f, g : X \rightarrow X$  defined by  $f(t) = \frac{3t}{4}$  and  $g(t) = \frac{t}{16}$ . Consider the function  $\psi$  and  $\phi$  defined as follows

$$\psi(t) = \frac{t}{5} \text{ and } \phi(t) = \frac{t}{3}.$$

Definition of  $\vartheta$ ,  $\cap_{V \in \vartheta} V = \Delta$  and this show that the uniform space  $(X, \vartheta)$  is Hausdorff uniform space. And also  $X$  is  $S$ -complete. On the other hand,  $p$  is an  $E$ -distance.  $f, g$  are commuting,  $p$ -continuous and  $f$  is  $g$ -nondecreasing. We have that for all  $x, y \in X$

$$p(fx, fy) \leq \ln(1 + \psi(p(x, y))) = F(\psi(p(gx, gy)), \phi(p(gx, gy))).$$

And 0 is the unique common fixed point of  $f$  and  $g$ .

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