Research Article

Presic Type Fixed Point Theorem for Four Maps in Metric Spaces

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We obtained a Presic type fixed point theorem for two pairs of jointly $2k$ -weakly compatible maps in metric spaces. We also have given an example to illustrate our main theorem.

1. Introduction and Preliminaries

Banach [1], in 1932, proved the following theorem, popularly known as Banach contraction principle.

Theorem 1. Let (X, d) be a complete metric space and let f be a self-mapping on X satisfying $d(fx, fy) \leq kd(x, y)$ for all $x, y \in X$, where $0 \leq k < 1$. Then f has a unique fixed point in X .

There are number of generalizations of such principle (see [2–12]). One such generalization is given by Presic [13] in 1965.

Let $f : X^k \rightarrow X$, where $k \geq 1$ is a positive integer. A point $x^* \in X$ is called a fixed point of f if $x^* = f(x^*, x^*, \dots, x^*)$. Consider the k -order nonlinear difference equation

$$x_{n+1} = f(x_{n-k+1}, x_{n-k+2}, \dots, x_n) \quad (1)$$

for $n = k-1, k, k+1, \dots$

with the initial values $x_0, x_1, x_2, \dots, x_{k-1} \in X$.

Equation (1) can be studied by means of fixed point theory in view of the fact that $x \in X$ is a solution of (1) if and only if x is a fixed point of f . One of the most important results in this direction is obtained by Presic [13] in the following way.

Theorem 2 (see [13]). Let (X, d) be a complete metric space, k be a positive integer, and $f : X^k \rightarrow X$. Suppose that

$$d(f(x_1, x_2, \dots, x_k), f(x_2, x_3, \dots, x_{k+1})) \leq \sum_{i=1}^k q_i d(x_i, x_{i+1}) \quad (2)$$

holds for all $x_1, x_2, \dots, x_k, x_{k+1} \in X$, where $q_i \geq 0$ and $\sum_{i=1}^k q_i \in [0, 1)$. Then f has a unique fixed point x^* . Moreover, for any arbitrary points $x_1, x_2, \dots, x_{k+1}$ in X , the sequence $\{x_n\}$ defined by $x_{n+k} = f(x_n, x_{n+1}, \dots, x_{n+k-1})$, for all $n \in \mathbb{N}$ converges to x^* .

Later Ćirić and Presic [14] generalized the above theorem as follows.

Theorem 3 (see [14]). Let (X, d) be a complete metric space, k be a positive integer, and $f : X^k \rightarrow X$. Suppose that

$$d(f(x_1, x_2, \dots, x_k), f(x_2, x_3, \dots, x_{k+1})) \leq \lambda \max \{d(x_i, x_{i+1}) : 1 \leq i \leq k\} \quad (3)$$

holds for all $x_1, x_2, \dots, x_k, x_{k+1}$ in X , where $\lambda \in [0, 1)$. Then f has a fixed point $x^* \in X$. Moreover, for any arbitrary points $x_1, x_2, \dots, x_{k+1}$ in X , the sequence $\{x_n\}$ defined by $x_{n+k} = f(x_n, x_{n+1}, \dots, x_{n+k-1})$, for all $n \in \mathbb{N}$ converges to x^* .

Moreover, if $d(f(u, u, \dots, u), f(v, v, \dots, v)) < d(u, v)$ holds for all $u, v \in X$ with $u \neq v$, then x^* is the unique fixed point of f .

Recently Rao et al. [2, 3] obtained some Presic type theorems for two and three maps in metric spaces. Now we give the following definition of [2, 3].

Definition 4. Let X be a nonempty set and $T : X^{2k} \rightarrow X$ and $f : X \rightarrow X$. The pair (f, T) is said to be $2k$ -weakly compatible if $f(T(x, x, \dots, x, x)) = T(fx, fx, \dots, fx, fx)$ whenever $x \in X$ such that $fx = T(x, x, \dots, x, x)$.

Using this definition, Rao et al. [2] proved the following.

Theorem 5 (see [2]). Let (X, d) be a metric space, k be a positive integer, and $S, T : X^{2k} \rightarrow X, f : X \rightarrow X$ be mappings satisfying

$$(1.4.1) \quad d(S(x_1, x_2, \dots, x_{2k}), T(x_2, x_3, \dots, x_{2k+1})) \leq \lambda \max\{d(fx_i, fx_{i+1}) : 1 \leq i \leq 2k\} \text{ for all } x_1, x_2, \dots, x_{2k}, x_{2k+1} \text{ in } X,$$

$$(1.4.2) \quad d(T(y_1, y_2, \dots, y_{2k}), S(y_2, y_3, \dots, y_{2k+1})) \leq \lambda \max\{d(fy_i, fy_{i+1}) : 1 \leq i \leq 2k\} \text{ for all } y_1, y_2, \dots, y_{2k}, y_{2k+1} \text{ in } X, \text{ where } 0 \leq \lambda < 1,$$

$$(1.4.3) \quad d(S(u, \dots, u), T(v, \dots, v)) < d(fu, fv), \text{ for all } u, v \in X \text{ with } u \neq v.$$

$$(1.4.4) \quad \text{Suppose that } f(X) \text{ is complete and either } (f, S) \text{ or } (f, T) \text{ is a } 2k\text{-weakly compatible pair.}$$

Then there exists a unique point $p \in X$ such that $fp = p = S(p, \dots, p) = T(p, \dots, p)$.

Now we give a definition of jointly $2k$ -weakly compatible pairs.

Definition 6. Let X be a nonempty set, k be a positive integer, $S, T : X^{2k} \rightarrow X$, and $f, g : X \rightarrow X$. The pairs (f, S) and (g, T) are said to be jointly $2k$ -weakly compatible pairs if $f(S(x, x, \dots, x)) = S(fx, fx, \dots, fx)$ and $g(T(x, x, \dots, x)) = T(gx, gx, \dots, gx)$ whenever there exists $x \in X$ such that $fx = S(x, x, \dots, x)$ and $gx = T(x, x, \dots, x)$.

In this paper, we obtain a Presic type theorem for four mappings satisfying a slight different contractive condition in metric spaces. We also give an example and two corollaries to our main theorem.

Now we prove our main result.

2. Main Result

Theorem 7. Let (X, d) be a complete metric space, k be a positive integer, and $S, T : X^{2k} \rightarrow X$ and $f, g : X \rightarrow X$ be mappings satisfying

$$(2.1.1) \quad S(X^{2k}) \subseteq g(X), T(X^{2k}) \subseteq f(X),$$

$$(2.1.2) \quad d(S(x_1, x_2, \dots, x_{2k-1}, x_{2k}), T(y_1, y_2, \dots, y_{2k-1}, y_{2k})) \leq \lambda \max\{d(gx_1, fy_1), d(fx_2, gy_2), d(gx_3, fy_3), d(fx_4, gy_4), \dots, d(gx_{2k-1}, fy_{2k-1}), d(fx_{2k}, gy_{2k})\} \\ \text{for all } x_1, x_2, \dots, x_{2k}, y_1, y_2, \dots, y_{2k} \in X \text{ and } 0 < \lambda < 1,$$

$$(2.1.3) \quad (f, S) \text{ and } (g, T) \text{ are jointly } 2k\text{-weakly compatible pairs.}$$

$$(2.1.4) \quad \text{Suppose } z = fp = gp \text{ for some } p \in X \text{ whenever there exists a sequence } \{y_{2k+n}\}_{n=1}^{\infty} \text{ in } X \text{ such that } \lim_{n \rightarrow \infty} y_{2k+n} = z \in X.$$

$$\text{Then } z \text{ is the unique point in } X \text{ such that } z = fz = gz = S(z, z, \dots, z) = T(z, z, \dots, z).$$

Proof. Suppose $x_1, x_2, \dots, x_{2k}$ are arbitrary points in X . From (2.1.1), define

$$\begin{aligned} y_{2k+2n-1} &= S(x_{2n-1}, x_{2n}, \dots, x_{2k+2n-2}) = gx_{2k+2n-1} \\ y_{2k+2n} &= T(x_{2n}, x_{2n+1}, \dots, x_{2k+2n-1}) = fx_{2k+2n} \end{aligned} \quad (4)$$

for $n = 1, 2, \dots$

Let

$$\begin{aligned} \alpha_{2n} &= d(fx_{2n}, gx_{2n+1}), \\ \alpha_{2n-1} &= d(gx_{2n-1}, fx_{2n}), \end{aligned} \quad (5)$$

$n = 1, 2, \dots$

Let $\theta = \lambda^{1/2k}$ and $\mu = \max\{\alpha_1/\theta, \alpha_2/\theta^2, \dots, \alpha_{2k}/\theta^{2k}\}$. Then $0 < \theta < 1$ and by selection of μ we have

$$\alpha_n \leq \mu\theta^n, \quad \text{for } n = 1, 2, \dots, 2k. \quad (6)$$

$$\begin{aligned} \alpha_{2k+1} &= d(gx_{2k+1}, fx_{2k+2}) = d(S(x_1, x_2, x_3, x_4, \dots, x_{2k-1}, x_{2k}), T(x_2, x_3, x_4, \dots, x_{2k}, x_{2k+1})) \leq \lambda \\ &\quad \cdot \max\{d(gx_1, fx_2), d(fx_2, gx_3), d(gx_3, fx_4), \\ &\quad d(fx_4, gx_5), \dots, d(gx_{2k-1}, fx_{2k}), d(fx_{2k}, gx_{2k+1})\} \\ &\quad \text{from (2.1.2)} \end{aligned} \quad (7)$$

$$= \lambda \max\{\alpha_1, \alpha_2, \alpha_3, \alpha_4, \dots, \alpha_{2k-1}, \alpha_{2k}\} \leq \lambda \max\{\mu\theta, \mu\theta^2, \mu\theta^3, \mu\theta^4, \dots, \mu\theta^{2k-1}, \mu\theta^{2k}\} \quad \text{from (6)}$$

$$= \lambda\mu\theta = \theta^{2k}\mu\theta = \mu\theta^{2k+1},$$

$$\begin{aligned} \alpha_{2k+2} &= d(fx_{2k+2}, gx_{2k+3}) = d(S(x_3, x_4, x_5, x_6, \dots, x_{2k+1}, x_{2k+2}), T(x_2, x_3, x_4, \dots, x_{2k}, x_{2k+1})) \leq \lambda \\ &\quad \cdot \max\{d(gx_3, fx_2), d(fx_4, gx_3), d(gx_5, fx_4), \\ &\quad d(fx_6, gx_5), \dots, d(gx_{2k+1}, fx_{2k}), \\ &\quad d(fx_{2k+2}, gx_{2k+3})\} \quad \text{from (2.1.2)} \end{aligned} \quad (8)$$

$$= \lambda \max\{\alpha_2, \alpha_3, \alpha_4, \alpha_5, \dots, \alpha_{2k}, \alpha_{2k+1}\} \leq \lambda \max\{\mu\theta^2, \mu\theta^3, \mu\theta^4, \mu\theta^5, \dots, \mu\theta^{2k}, \mu\theta^{2k+1}\} \quad \text{from (6), (7)}$$

$$= \lambda\mu\theta^2 = \theta^{2k}\mu\theta^2 = \mu\theta^{2k+2}.$$

Continuing in this way, we get

$$\alpha_n \leq \mu\theta^n \quad \text{for } n = 1, 2, \dots \quad (9)$$

Now consider

$$\begin{aligned} d(y_{2k+2n-1}, y_{2k+2n}) &= d(S(x_{2n-1}, x_{2n}, x_{2n+1}, x_{2n+2}, \dots, \\ &\quad x_{2k+2n-3}, x_{2k+2n-2}), T(x_{2n}, x_{2n+1}, x_{2n+2}, x_{2n+3}, \dots, \\ &\quad x_{2k+2n-2}, x_{2k+2n-1})) \leq \lambda \max\{d(gx_{2n-1}, fx_{2n}), \\ &\quad d(fx_{2n}, gx_{2n+1}), d(gx_{2n+1}, fx_{2n+2}), \\ &\quad d(fx_{2n+2}, gx_{2n+3}), \dots, d(gx_{2k+2n-3}, fx_{2k+2n-2}), \\ &\quad d(fx_{2k+2n-2}, gx_{2k+2n-1})\} = \lambda \max\{\alpha_{2n-1}, \alpha_{2n}, \alpha_{2n+1}, \\ &\quad \alpha_{2n+2}, \dots, \alpha_{2k+2n-3}, \alpha_{2k+2n-2}\} \leq \lambda \max\{\mu\theta^{2n-1}, \mu\theta^{2n}, \\ &\quad \mu\theta^{2n+1}, \mu\theta^{2n+2}, \dots, \mu\theta^{2k+2n-3}, \mu\theta^{2k+2n-2}\} \quad \text{from (9)} \\ &= \lambda\mu\theta^{2n-1} = \theta^{2k}\mu\theta^{2n-1} = \mu\theta^{2k+2n-1}. \end{aligned} \quad (10)$$

Also

$$\begin{aligned} d(y_{2k+2n}, y_{2k+2n+1}) &= d(S(x_{2n+1}, x_{2n+2}, x_{2n+3}, x_{2n+4}, \dots, \\ &\quad x_{2k+2n-1}, x_{2k+2n}), T(x_{2n}, x_{2n+1}, x_{2n+2}, x_{2n+3}, \dots, \\ &\quad x_{2k+2n-2}, x_{2k+2n-1})) \leq \lambda \max\{d(gx_{2n+1}, fx_{2n}), \\ &\quad d(fx_{2n+2}, gx_{2n+1}), d(gx_{2n+3}, fx_{2n+2}), \\ &\quad d(fx_{2n+4}, gx_{2n+3}), \dots, d(gx_{2k+2n-1}, fx_{2k+2n-2}), \\ &\quad d(fx_{2k+2n}, gx_{2k+2n-1})\} = \lambda \max\{\alpha_{2n}, \alpha_{2n+1}, \alpha_{2n+2}, \\ &\quad \alpha_{2n+3}, \dots, \alpha_{2k+2n-2}, \alpha_{2k+2n-1}\} \leq \lambda \max\{\mu\theta^{2n}, \mu\theta^{2n+1}, \\ &\quad \mu\theta^{2n+2}, \mu\theta^{2n+3}, \dots, \mu\theta^{2k+2n-2}, \mu\theta^{2k+2n-1}\} \quad \text{from (9)} \\ &= \lambda\mu\theta^{2n} = \theta^{2k}\mu\theta^{2n} = \mu\theta^{2k+2n}. \end{aligned} \quad (11)$$

Thus from (10) and (11) we have

$$d(y_{2k+n}, y_{2k+n+1}) \leq \mu\theta^{2k+n} \quad \text{for } n = 1, 2, 3, \dots \quad (12)$$

Now from $m > n$ consider

$$\begin{aligned} d(y_{2k+n}, y_{2k+m}) &\leq d(y_{2k+n}, y_{2k+n+1}) \\ &\quad + d(y_{2k+n+1}, y_{2k+n+2}) \\ &\quad + d(y_{2k+n+2}, y_{2k+n+3}) + \dots \\ &\quad + d(y_{2k+m-1}, y_{2k+m}) \\ &\leq \mu\theta^{2k+n} + \mu\theta^{2k+n+1} + \mu\theta^{2k+n+2} + \dots \\ &\quad + \mu\theta^{2k+m-1} \quad \text{from (12)} \\ &\leq \mu\theta^{2k} \frac{\theta^n}{1-\theta} \longrightarrow 0 \\ &\quad \text{as } n \longrightarrow \infty, m \longrightarrow \infty. \end{aligned} \quad (13)$$

Hence $\{y_{2k+n}\}$ is a Cauchy sequence in X . Since X is complete there exists $z \in X$ such that $y_{2k+n} \rightarrow z$ as $n \rightarrow \infty$. From (2.1.4), there exists $u \in X$ such that

$$z = fu = gu. \quad (14)$$

Now consider

$$\begin{aligned} d(S(u, u, \dots, u, u), y_{2k+2n}) &= d(S(u, u, \dots, u, u), \\ &\quad T(x_{2n}, x_{2n+1}, \dots, x_{2k+2n-2}, x_{2k+2n-3})) \leq \lambda \\ &\quad \cdot \max\{d(gp, fx_{2n}), d(fp, gx_{2n+1}), d(gp, fx_{2n+2}), \\ &\quad d(fp, gx_{2n+3}), \dots, d(gp, fx_{2k+2n-2}), \\ &\quad d(fp, gx_{2k+2n-1})\}. \end{aligned} \quad (15)$$

Letting $n \rightarrow \infty$ and using (14) $d(S(u, u, \dots, u, u), fu) \leq 0$ so that

$$fu = S(u, u, \dots, u, u). \quad (16)$$

Similarly we have

$$gu = T(u, u, \dots, u, u). \quad (17)$$

Since (f, S) and (g, T) are jointly $2k$ -weakly compatible pairs, we have

$$fz = f(fu) = f(S(u, u, \dots, u, u)) = S(fu, fu, \dots, \quad (18)$$

$$fu, fu) = S(z, z, \dots, z, z),$$

$$gz = T(z, z, \dots, z, z) \quad (19)$$

$$d(fz, z) = d(fz, gu) = d(S(z, z, \dots, z, z), T(u, u, \dots, u, u)) \quad \text{from (18), (17)}$$

$$\leq \lambda \max\{d(gz, fu), d(fz, gu), d(gz, fu), d(fz, gu), \quad (20)$$

$$\dots, d(gz, fu), d(fz, gu)\} = \lambda \max\{d(gz, z),$$

$$d(fz, z)\} \quad \text{from (14)}.$$

Similarly, we have

$$d(gz, z) \leq \lambda \max\{d(z, fz), d(z, gz)\}. \quad (21)$$

From (20) and (21) we have

$$\begin{aligned} \max\{d(z, fz), d(z, gz)\} \\ \leq \lambda \max\{d(z, fz), d(z, gz)\} \end{aligned} \quad (22)$$

which in turn yields that

$$\begin{aligned} fz &= z, \\ gz &= z. \end{aligned} \quad (23)$$

From (18), (19), and (23), we have

$$z = fz = gz = S(z, z, \dots, z, z) = T(z, z, \dots, z, z). \quad (24)$$

Suppose there exists $z' \in X$ such that

$$\begin{aligned} z' &= fz' = gz' = S(z', z', \dots, z', z') \\ &= T(z', z', \dots, z', z'). \end{aligned} \quad (25)$$

Then from (2.1.2) we have

$$\begin{aligned} d(z, z') &= d(S(z, z, \dots, z, z), T(z', z', \dots, z', z')) \\ &\leq \lambda \max \{d(gz, fz'), d(fz, gz'), \dots, d(gz, fz'), \\ &\quad d(fz, gz')\} = \lambda d(z, z'). \end{aligned} \quad (26)$$

This implies that $z' = z$.

Thus z is the unique point in X satisfying (24). $\square$

Now we give an example to illustrate our main Theorem 7.

Example 8. Let $X = [0, 1]$, $k = 1$, and $d(x, y) = |x - y|$. Define $S(x, y) = (3x^2 + 2y)/72$, $T(x, y) = (2x + 3y^2)/72$, $fx = x/6$, and $gx = x^2/4$ for all $x, y \in X$.

Then, for all $x_1, x_2, y_1, y_2 \in X$, we have

$$\begin{aligned} d(S(x_1, x_2), T(y_1, y_2)) &= \left| \frac{3x_1^2 + 2x_2}{72} - \frac{2y_1 + 3y_2^2}{72} \right| \\ &= \frac{1}{72} |(3x_1^2 - 2y_1) + (2x_2 - 3y_2^2)| \\ &\leq \frac{1}{72} (|3x_1^2 - 2y_1| + |2x_2 - 3y_2^2|) \\ &\leq \frac{1}{36} \max \{|3x_1^2 - 2y_1|, |2x_2 - 3y_2^2|\} \\ &= \frac{1}{3} \max \{d(gx_1, fy_1), d(fx_2, gy_2)\}. \end{aligned} \quad (27)$$

Thus the condition (2.1.2) of Theorem 7 is satisfied. One can easily verify the remaining conditions of Theorem 7. Clearly, 0 is the unique point in X such that $0 = f0 = g0 = S(0, 0, \dots, 0, 0) = T(0, 0, \dots, 0, 0)$.

Corollary 9. Let (X, d) be a metric space and $S, T : X^{2k} \rightarrow X$ and $f : X \rightarrow X$ be mappings satisfying

- (2.3.1) $S(X^{2k}) \subseteq f(X)$, $T(X^{2k}) \subseteq f(X)$,
- (2.3.2) $d(S(x_1, x_2, \dots, x_{2k-1}, x_{2k}), T(y_1, y_2, \dots, y_{2k-1}, y_{2k})) \leq \lambda \max \{d(fx_i, fy_i) / 1 \leq i \leq 2k\}$ for all $x_1, x_2, \dots, x_{2k}, y_1, y_2, \dots, y_{2k} \in X$ and $0 < \lambda < 1$,
- (2.3.3) $f(X)$ is a complete subspace of X ,
- (2.3.4) the pairs (f, S) or (f, T) is $2k$ -weakly compatible.

Then there exists a unique $u \in X$ such that $u = fu = S(u, u, \dots, u, u) = T(u, u, \dots, u, u)$.

Corollary 10. Let (X, d) be a complete metric space and $S, T : X^{2k} \rightarrow X$ be mappings satisfying

- (2.4.1) $d(S(x_1, x_2, \dots, x_{2k-1}, x_{2k}), T(y_1, y_2, \dots, y_{2k-1}, y_{2k})) \leq \lambda \max \{d(x_i, y_i) / 1 \leq i \leq 2k\}$ for all $x_1, x_2, \dots, x_{2k}, y_1, y_2, \dots, y_{2k} \in X$ and $0 < \lambda < 1$.

Then there exists a unique $u \in X$ such that $u = S(u, u, \dots, u) = T(u, u, \dots, u)$.

Remark 11. Corollaries 9 and 10 are slight variant of theorems of [2, 3].

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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