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Fixed Points of Mappings Satisfying Implicit F-Contractive Conditions

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ABSTRACT: This paper presents a generalized fixed point theorem in metric spaces or ordered metric spaces using an implicit relation to unify various F-contractive type mappings. Relying only on the strict monotonicity of the auxiliary function F, the result extends previous work and includes corollaries that demonstrate its generality. The approach simplifies the analysis by eliminating the need for separate proofs for each type of contraction.

Keywords: Metric spaces, ordered metric spaces, fixed point, self mappings, F-contractive type mappings, implicit relation.

Contents

1. Introduction and Preliminary

In 2012, Wardowski [15] introduced a new type of contractions called F-contraction as a generalization of Banach contraction and prove a new fixed point theorem concerning F-contractions. In this way, he defined a class of function F as follows.

Consider $F:(0,+\infty)\to\mathbb{R}$ is a mapping satisfying the following conditions:

(F_1) F is strictly increasing.

(F_2) For each sequence $\{\alpha_n\}_{n=1}^{+\infty}$ of positive numbers, $\lim\limits_{n\to+\infty}\alpha_n=0$ if and only if $\lim\limits_{n\to+\infty}F(\alpha_n)=-\infty$;

(F_3) There exists $k\in(0,1)$ such that $\lim\limits_{\alpha\to0^+}\alpha^kF(\alpha)=0$.

We denote by $\mathcal{F}$, the set of all functions satisfying the conditions (F_1)-(F_3).

Wardowski [15] stated a modified version of the Banach contraction principle as follows.

Theorem 1.1 *Let (X,d) be a complete metric space and $T:X\to X$ is a given mapping. Assume that there exist $\tau>0$ and a mapping $F\in\mathcal{F}$ such that for all $x,y\in X$:*

$$d(Tx,Ty)>0 \implies \tau+F\left(d(Tx,Ty)\right)\le F\left(d(x,y)\right).$$

Then T has a unique fixed point in X.

Several fixed point results have been established by using F-contractions types, with F in $\mathcal{F}$ (see [1,3,16] and references therein).

We recall the following two properties of sequences in metric spaces that have often been used, sometimes implicitly, in proving fixed point results (see [12] for the first property and [10] for the second one).

Lemma 1.1 *Let (x_n) be a Picard sequence of a self-map T in a metric space (X,d) (i.e., $x_n=Tx_{n-1}$, $n\in\mathbb{N}$). If $d(x_{n+1},x_n)<d(x_n,x_{n-1})$ holds for each $n\in\mathbb{N}$, then $x_n\neq x_m$ whenever $n\neq m$.*

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Lemma 1.2 *Let (x_n) be a sequence in metric space (X, d) such that $\lim_{n\to+\infty} d(x_n, x_{n+1}) = 0$. If (x_n) is not a Cauchy in (X, d), then there exists $\varepsilon > 0$ and two sequences (n_k) and (m_k) of positive integers such that $n_k > m_k > k$, and the sequences:*

$$d(x_{n_k}, x_{m_k}), d(x_{n_k+1}, x_{m_k}), d(x_{n_k}, x_{m_k-1}), d(x_{n_k+1}, x_{m_k-1}), d(x_{n_k+1}, x_{m_k+1}), \ldots$$

tend to ε, as $k \to +\infty$.

The existence of fixed points of self-mappings defined on certaint type of ordered sets plays an important role in the order theoretic approach. It has been initiated in 2004 by Ran and Reurings [11], and further studied by Nieto and odríguez-López [7]. Then, several interesting and valuable results have appeared in this direction (see [2,3,8] and references therein).

An ordered metric space is defined as a 3-tuple $(X, d, \preceq)$, where:

- (X, d) is a metric space,
- $(X, \preceq)$ is partially ordered.

$x, y \in X$ are called comparable if $x \preceq y$ or $y \preceq x$ holds. If $(X, \preceq)$ be a partially ordered set, A self-mapping T on X is called non-decreasing if $Tx \preceq Ty$ whenever $x \preceq y$ for all $x, y \in X$. An ordered metric space $(X, d, \preceq)$ is regular if, for every non-decreasing sequence (x_n) in X convergent to some $x \in X$, we have $x_n \preceq x$ for all $n \in \mathbb{N} \cup \{0\}$.

Recently, using the two lemmas mentioned above and the fundamental property of a strictly increasing function F, namely, that F admits left and right limits at every point r in $(0, +\infty)$ satisfying $F(r^-) \leq F(r) \leq F(r^+)$, several works appear by proving and improving fixed point theorem using only the strict monotonicity of F (see [4,5,6,9,13,14] and references therein).

2. Fixed Point Theorems in Metric Space

We begin by stating assumptions about the implicit relation, which generalize the specific types of contractions discussed in the introduction.

Let Φ the set of all continuous function $\phi : \mathbb{R}_+^5 \to \mathbb{R}$ such that:

(ϕ_1) The function ϕ is non-decreasing in the fourth variable.

(ϕ_2) for all $u, v \geq 0$, we have

$$\phi(v, v, u, u + v, 0) \leq \max\{u, v\}.$$

(ϕ_3) For all $u \geq 0$, $\phi(u, 0, 0, u, u) = u$.

Example 2.1 $\phi(t_1, t_2, t_3, t_4, t_5) = t_1$.

Example 2.2 $\phi(t_1, t_2, t_3, t_4, t_5) = \max\left\{t_1, t_2, t_3, \frac{t_4+t_5}{2}\right\}$.

Example 2.3 $\phi(t_1, t_2, t_3, t_4, t_5) = t_1 + L\min\{t_2, t_3, t_4, t_5\}$, *with* $L \geq 0$.

Example 2.4 $\phi(t_1, t_2, t_3, t_4, t_5) = \max\left\{t_1, t_2, t_3, \frac{t_4}{2}, \frac{t_5}{2}\right\}$

Theorem 2.1 *Let (X, d) be a complete metric space and let $T : X \to X$ be a given mapping. If there exist $\tau > 0$ and a strictly increasing mapping $F : (0, +\infty) \to \mathbb{R}$ such that for all $x, y \in X$, with $d(Tx, Ty) > 0$:*

$$\tau + F(d(Tx, Ty)) \leq F\left(\phi\left(\begin{array}{c} d(x, y), d(x, Tx), d(y, Ty), \\ d(x, Ty), d(y, Tx) \end{array}\right)\right) \tag{2.1}$$

where $\phi \in \Phi$. If T or F is continuous, then T has a unique fixed point in X.

Proof: Let $x_0 \in X$, and let (x_n) be the Picard sequence of initial point x_0, that is, $x_n = T^n x_0 = Tx_{n-1}$. If $x_n = x_{n-1}$ for some $n \in \mathbb{N}$, then x_n is a fixed point of T. Throughout the proof, we assume that $x_n \neq x_{n-1}$ for all $n \in \mathbb{N}$. According to (2.1), with $x = x_{n-1}$ and $y = x_n$ and since $d(Tx_{n-1}, Tx_n) = d(x_n, x_{n+1}) > 0$, we get

$$\tau + F\left(d(Tx_{n-1}, Tx_n)\right) \leq F\left(\phi\left(\begin{array}{c} d(x_{n-1}, x_n), d(x_{n-1}, Tx_{n-1}), d(x_n, Tx_n), \\ d(x_{n-1}, Tx_n), d(x_n, Tx_{n-1}) \end{array}\right)\right)$$

This simplifies to

$$\tau + F\left(d(x_n, x_{n+1})\right) \leq F\left(\phi\left(\begin{array}{c} d(x_{n-1}, x_n), d(x_{n-1}, x_n), d(x_n, x_{n+1}), \\ d(x_{n-1}, x_{n+1}), d(x_n, x_n) \end{array}\right)\right)$$

Using (ϕ_1) and the property of F, it follows that

$$\tau + F\left(d(x_n, x_{n+1})\right) \leq F\left(\phi\left(\begin{array}{c} d(x_{n-1}, x_n), d(x_{n-1}, x_n), d(x_n, x_{n+1}), \\ d(x_{n-1}, x_n) + d(x_n, x_{n+1}), 0 \end{array}\right)\right). \tag{2.2}$$

From (ϕ_2), we deduce that

$$\tau + F\left(d(x_n, x_{n+1})\right) \leq F\left(\max\left\{d(x_n, x_{n+1}), d(x_{n-1}, x_n)\right\}\right). \tag{2.3}$$

If there exists $n \in \mathbb{N}$ such that $\max\left\{d(x_n, x_{n+1}), d(x_{n-1}, x_n)\right\} = d(x_n, x_{n+1})$, then (2.3) becomes

$$\tau + F\left(d(x_n, x_{n+1})\right) \leq F\left(d(x_n, x_{n+1})\right)$$

which is a contradiction with $\tau > 0$. Therefore, $\max\left\{d(x_n, x_{n+1}), d(x_{n-1}, x_n)\right\} = d(x_{n-1}, x_n)$ for all $n \in \mathbb{N}$. Thus, from (2.3), we have

$$\tau + F\left(d(x_n, x_{n+1})\right) \leq F\left(d(x_{n-1}, x_n)\right). \tag{2.4}$$

Since $\tau > 0$ and F is strictly increasing, we deduce that

$$d(x_n, x_{n+1}) < d(x_{n-1}, x_n), \quad n \in \mathbb{N}.$$

It follows by Lemma 1.1 that $x_n \neq x_m$ whenever $n \neq m$. Also, the sequence $((d(x_n, x_{n+1}))$ must converge to some $d \geq 0$ as well as $d(x_n, x_{n+1}) > d$ for all $n \in \mathbb{N} \cup \{0\}$. If $d > 0$, then, passing to the limit when $n \to +\infty$ in (2.4), we get

$$\tau + F\left(d^+\right) \leq F\left(d^+\right)$$

which is in contradiction with $\tau > 0$. Therefore, $\lim\limits_{n \to +\infty} d(x_n, x_{n+1}) = 0$. Suppose now that (x_n) is not a Cauchy sequence and consider the sequences (m_k) and (n_k) that satisfy conditions as in Lemma 1.2. Since $n_k > m_k$, it follows that $x_{m_k} \neq x_{n_k}$, hence we can use contractive condition (2.1) with $x = x_{n_k}$ and $y = x_{m_k}$. We obtain that

$$\tau + F\left(d(Tx_{n_k}, Tx_{m_k})\right) \leq F\left(\phi\left(\begin{array}{c} d(x_{n_k}, x_{m_k}), d(x_{n_k}, Tx_{n_k}), d(x_{m_k}, Tx_{m_k}), \\ d(x_{n_k}, Tx_{m_k}), d(x_{m_k}, Tx_{n_k}) \end{array}\right)\right).$$

This simplifies to

$$\tau + F\left(d(x_{n_k+1}, x_{m_k+1})\right) \leq F\left(\phi\left(\begin{array}{c} d(x_{n_k}, x_{m_k}), d(x_{n_k}, x_{n_k+1}), d(x_{m_k}, x_{m_k+1}), \\ d(x_{n_k}, x_{m_k+1}), d(x_{m_k}, x_{n_k+1}) \end{array}\right)\right). \tag{2.5}$$

According to Lemma 1.2, the continuity of ϕ and (ϕ_3), we obtain that

$$\phi\left(\begin{array}{c} d(x_{n_k}, x_{m_k}), d(x_{n_k}, x_{n_k+1}), d(x_{m_k}, x_{m_k+1}), \\ d(x_{n_k}, x_{m_k+1}), d(x_{m_k}, x_{n_k+1}) \end{array}\right) \to \phi\left(\varepsilon, 0, 0, \varepsilon, \varepsilon\right) = \varepsilon$$

as $k \to +\infty$. Further, (2.5) yields

$$\tau + F\left(\varepsilon^{+}\right) \leq F\left(\varepsilon\right)$$

which is in contradiction with $\tau > 0$. Hence, (x_n) is a Cauchy sequence and, since (X, d) is complete, it converges to some $x \in X$. If T is continuous, since $x_{n+1} = Tx_n$, we deduce that $Tx = x$. Now, we suppose that F is continuous. If there exists a sequence (n_k) of natural numbers such that $x_{n_k+1} = Tx_{n_k} = Tx$, then $\lim\limits_{k\to+\infty} x_{n_k+1} = x$, so $Tx = x$. Otherwise, there exists $N \in \mathbb{N}$ such that $x_{n+1} = Tx_n \neq Tx$, $\forall n \geq N$. Assume that $Tx \neq x$. According to (2.1), with $x = x_{n-1}$ and $y = x$, we have

$$\tau + F\left(d(Tx_n, Tx)\right) \leq F\left(\phi\left(\begin{array}{c} d(x_n, x), d(x_n, Tx_n), d(x, Tx), \\ d(x_n, Tx), d(x, Tx_n) \end{array}\right)\right).$$

This simplifies to

$$\tau + F\left(d(x_{n+1}, Tx)\right) \leq F\left(\phi\left(\begin{array}{c} d(x_n, x), d(x_n, x_{n+1}), d(x, Tx), \\ d(x_n, Tx), d(x, x_{n+1}) \end{array}\right)\right).$$

On taking limit as $n \to +\infty$, we get

$$\tau + F\left(d(x, Tx)\right) \leq F\left(\phi\left(\begin{array}{c} 0, 0, d(x, Tx), \\ d(x, Tx), 0 \end{array}\right)\right).$$

From (ϕ_2) and the property of F, we deduce that

$$\tau + F\left(d(x, Tx)\right) \leq F\left(d(x, Tx)\right).$$

which is in contradiction with $\tau > 0$. Therefore, $Tx = x$.

Finally, suppose that $x, y \in X$ are two distinct fixed point of T in X. Since $Tx = x \neq y = Ty$, we have

$$\tau + F\left(d(Tx, Ty)\right) \leq F\left(\phi\left(\begin{array}{c} d(x, y), d(x, Tx), d(y, Ty), \\ d(x, Ty), d(y, Tx) \end{array}\right)\right).$$

This simplifies to

$$\tau + F\left(d(x, y)\right) \leq F\left(\phi\left(\begin{array}{c} d(x, y), 0, 0, \\ d(x, y), d(y, x) \end{array}\right)\right).$$

From (ϕ_3), we deduce that

$$\tau + F\left(d(x, y)\right) \leq F\left(d(x, y)\right).$$

which is in contradiction with $\tau > 0$. Therefore, $x = y$. □

Corollary 2.1 (Theorem 2.3 in [4]) *Let (X, d) be a complete metric space and let $T : X \to X$ be a given mapping. If there exist $\tau > 0$ and a strictly increasing mapping $F : (0, +\infty) \to \mathbb{R}$ such that for all $x, y \in X$, with $d(Tx, Ty) > 0$:*

$$\tau + F\left(d(Tx, Ty)\right) \leq F\left(d(x, y)\right). \tag{2.6}$$

Then T has a unique fixed point in X.

Proof: Apply Theorem 2.1, with ϕ as in Example 2.1 and note that the condition (2.6) implies the continuity of T. □

Corollary 2.2 (Theorem 3.3 in [5]) *Let (X, d) be a complete metric space and let $T : X \to X$ be a given mapping. If there exist $\tau > 0$ and a strictly increasing mapping $F : (0, +\infty) \to \mathbb{R}$ such that for all $x, y \in X$, with $d(Tx, Ty) > 0$:*

$$\tau + F\left(d(Tx, Ty)\right) \leq F\left(\max\left\{d(x, y), d(x, Tx), d(y, Ty), \frac{d(x, Ty) + d(y, Tx)}{2}\right\}\right).$$

If T or F is continuous, then T has a unique fixed point in X.

Proof: Apply Theorem 2.1, with ϕ as in Example 2.2. □

Remark 2.1 *Corollary 2.1 is a consequence of Corollary 2.2. Indeed, let $x, y \in X$, with $d(Tx,Ty) > 0$. If the condition of Corollary 2.1 is satisfied, then*

$$\tau + F\left(d(Tx,Ty)\right) \leq F\left(d(x,y)\right).$$

Since $d(x,y) \leq \max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)+d(y,Tx)}{2}\right\}$ and F is strictly increasing, it follows that

$$F\left(d(x,y)\right) \leq F\left(\max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)+d(y,Tx)}{2}\right\}\right).$$

Therefore

$$\tau + F\left(d(Tx,Ty)\right) \leq F\left(\max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)+d(y,Tx)}{2}\right\}\right).$$

Then the condition of Corollary 2.2 is satisfied, so we can get this conclusion.

Corollary 2.3 *Let (X,d) be a complete metric space and let $T : X \to X$ be a given mapping. If there exist $\tau > 0$ and a strictly increasing mapping $F : (0,+\infty) \to \mathbb{R}$ such that for all $x, y \in X$, with $d(Tx,Ty) > 0$:*

$$\tau + F\left(d(Tx,Ty)\right) \leq F\left(d(x,y) + L\min\left\{d(x,Tx), d(y,Ty), d(x,Ty), d(y,Tx)\right\}\right),$$

with $L \geq 0$. If T or F is continuous, then T has a unique fixed point in X.

Proof: Apply Theorem 2.1, with ϕ as in Example 2.3. □

Corollary 2.4 *Let (X,d) be a complete metric space and let $T : X \to X$ be a given mapping. If there exist $\tau > 0$ and a strictly increasing mapping $F : (0,+\infty) \to \mathbb{R}$ such that for all $x, y \in X$, with $d(Tx,Ty) > 0$:*

$$\tau + F\left(d(Tx,Ty)\right) \leq F\left(\max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)}{2}, \frac{d(y,Tx)}{2}\right\}\right).$$

If T or F is continuous, then T has a unique fixed point in X.

Proof: Apply Theorem 2.1, with ϕ as in Example 2.4. □

Example 2.5 *Let $X = \{0,1,3\}$, $d(x,y) = |x-y|$. Then (X,d) is a complete metric space. Define the function $T : X \to X$ as follows: $T0 = T1 = 1$ and $T3 = 0$.*

First observe that

$$d(Tx,Ty) > 0 \iff [(x = 0 \wedge y = 3) \vee (x = 1 \wedge y = 3) \vee (x = 3 \wedge y = 0) \vee (x = 3 \wedge y = 1)]$$

Case 1. *$x = 0 \wedge y = 3$. We have*

$$d(T0,T3) = 1.$$

And

$$\max\left\{d(0,3), d(0,T0), d(3,T3), \frac{d(0,T3)}{2}, \frac{d(3,T0)}{2}\right\} = 3$$

Case 2. *$x = 1 \wedge y = 3$. We have*

$$d(T1,T3) = 1.$$

And

$$\max\left\{d(1,3), d(1,T1), d(3,T3), \frac{d(1,T3)}{2}, \frac{d(3,T1)}{2}\right\} = 3$$

Similarly, if $x = 3 \wedge y = 0$ as well as $x = 3 \wedge y = 1$, we get

$$d(Tx, Ty) = 1.$$

And,

$$\max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)}{2}, \frac{d(y,Tx)}{2}\right\} = 3.$$

Now, we see that in all cases, the condition

$$\tau + F\left(d(Tx,Ty)\right) \leq F\left(\max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)}{2}, \frac{d(y,Tx)}{2}\right\}\right).$$

i.e,

$$\tau + F(1) \leq F(3).$$

is possible for any strictly increasing function F, and any $\tau \in (0, F(3) - F(1)]$. Therefore all conditions of Corollary 2.4 are satisfied, then T has a unique fixed point in X.

3. Fixed Point Theorems in Ordered Metric Space

Theorem 3.1 *Let $(X, d, \preceq)$ be an ordered complete metric space and let $T : X \to X$ be a non-decreasing mapping. If there exist $\tau > 0$ and a strictly increasing mapping $F : (0, +\infty) \to \mathbb{R}$ such that for all comparable $x, y \in X$, with $d(Tx, Ty) > 0$, the condition (2.1) is satisfied, with $\phi \in \Phi$. Suppose that:*

(a) there exists $x_0 \in X$ such that $x_0 \preceq Tx_0$;

(b) one of the following conditions is valid:

- *(b_1) T is continuous;*
- *(b_2) X is regular and F is continuous.*

Then T has a fixed point. Moreover, the set of fixed points of T is well ordered if and only if T has a unique fixed point.

Proof: Let $x_0 \in X$ be such that $x_0 \preceq Tx_0$, and let (x_n) be the Picard sequence of initial point x_0, that is, $x_n = T^n x_0 = Tx_{n-1}$. If $x_n = x_{n-1}$ for some $n \in \mathbb{N}$, then x_n is a fixed point of T. Throughout the proof, we assume that $x_n \neq x_{n-1}$ for all $n \in \mathbb{N}$. As T is non-decreasing and $x_0 \preceq Tx_0$, we deduce that

$$x_0 \preceq x_1 \preceq \ldots \preceq x_n \preceq \ldots, \tag{3.1}$$

that is, x_{n-1} and x_n are comparable for all $n \in \mathbb{N}$.

Proceeding as in the proof of Theorem 2.1, we obtain that x_n is a Cauchy sequence. As X is a complete ordered metric space there exists $x \in X$ such that $x_n \to x$ as $n \to +\infty$. If T is continuous, since $x_{n+1} = Tx_n$, we deduce that $Tx = x$. Now, we suppose that X is regular and F is continuous. Since X is regular, from (3.1), we deduce that x_n and x are comparable. If there exists a sequence (n_k) of natural numbers such that $x_{n_k+1} = Tx_{n_k} = Tx$, then $\lim_{k\to+\infty} x_{n_k+1} = x$, so $Tx = x$. Otherwise, there exists $N \in \mathbb{N}$ such that $x_{n+1} = Tx_n \neq Tx$, $\forall n \geq N$. Assume that $Tx \neq x$.

Proceeding again as in the proof of Theorem 2.1, we get that $Tx = x$.

Finally, assume that the set of fixed points of T is well ordered and suppose that $x, y \in X$ are two distinct fixed point of T in X.

Proceeding again as in the proof of Theorem 2.1, we get that $x = y$. Conversely, if T has a unique fixed point, then the set of fixed points of T, being a singleton, is well ordered. □

Similarly, for each example of function $\phi \in \Phi$, we obtain a fixed point result for F-contractive mappings in ordered metric spaces

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