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Common Fixed Point Theorem for Fuzzy Mappings in Banach Spaces

Sayan Jana[1], Sanjib Kumar Datta[2], Prosenjit Sen[3], Mohit Sarkar[4]
[1]*Department of Mathematics, Vivekananda College (Thakurpukur), 269 Diamond Harbour Road, Thakurpukur, Kolkata-700063*
[2]*Department of Mathematics, University of Kalyani, P.O.: Kalyani, Dist: Nadia, PIN: 741235, West Bengal, India*
[3]*Department of Mathematics, OmDayal Group of Institutions, Uluberia, Howrah - 711316, India*
[4]*Department of Mathematics, Fakir Chand College (Diamond Harbour), Diamond Harbour, Dist: South 24 Parganas, PIN: 743331, West Bengal, India*

Abstract: ***This paper aims to establish a common fixed point theorem for fuzzy mappings in the setting of a complete normed linear space, that is, a Banach space. The result obtained here extends and generalizes several existing theorems available in the literature on this subject. To illustrate the usefulness and validity of the main theorem, a suitable example is also presented.***
Keywords: Fuzzy mappings, Fixed point, Hausdorff distance, Normed linear spaces, Fuzzy fixed point.
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I. INTRODUCTION

Fixed point theory is one of the most active and fascinating branches of modern mathematical research. It plays a central role in the study of existence and uniqueness of solutions to a wide variety of problems arising in mathematics, physics, engineering, medicine and the social sciences. In particular, many mathematical models can be formulated in terms of nonlinear integral equations, functional equations and differential equations. The Banach contraction principle has been extended in several directions by altering the ambient space and the contractive conditions.

The notion of a fuzzy set was introduced by Zadeh [14]. Later, Weiss [13] established several fixed point results for fuzzy mappings in metric spaces. Heilpern [6] introduced fuzzy contraction mappings and proved a fixed point theorem for such mappings, which may be regarded as a fuzzy version of Nadler's fixed point theorem for multivalued mappings [10]. Related developments on fuzzy mappings can be found in [8] and [9].

In this paper, we proved a common fixed point theorem for fuzzy mappings in normed linear spaces. We also present an example to illustrate the applicability of the obtained results.

The results obtained here for fuzzy mappings in normed linear spaces under suitable contractive conditions are useful for the computation of Hausdorff dimensions, which in turn have applications in high-energy physics. They are also relevant in the study of geometric problems arising from the use of fuzzy sets.

II. PRELIMINARIES

Definition 2.1. *Let X be a nonempty vector space over the field* R. *A mapping $\|\cdot\| : X \to \mathrm{R}$ is said to be a norm if it satisfies the following properties:*

1. $\|x\| \geq 0$ *for every* $x \in X$,
2. $\|x\| = 0$ *if and only if* $x = 0$,
3. $\|x + y\| \leq \|x\| + \|y\|$ *for all* $x,y \in X$,
4. $\|\alpha x\| = |\alpha|\|x\|$ *for all* $x \in X$ *and every* $\alpha \in \mathrm{R}$.

In this case, $\|\cdot\|$ is called a norm on X and the pair $(X,\|\cdot\|)$ is called a normed linear space.

Example 1. *Consider* $X = \mathrm{R}$, *the vector space of all real numbers over* R *and define* $\|\cdot\| : X \to \mathrm{R}$ *by*

$$\|x\| = \sqrt{x \cdot x} \qquad \forall x \in X.$$

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Then $\|\cdot\|$ *is a norm on X.*

Definition 2.2. *Let* $(X,\|\cdot\|)$ *be a normed linear space and let* $A \subseteq X$.

(i) A point $a \in A$ *is called an interior point of A if there exists some* $r > 0$ *such that*

$$B(a,r) = \{x \in X : \|x - a\| < r\} \subseteq A.$$

The set A is called open if every point of A is an interior point of A. The set $B(a,r)$ *is called an open ball and its closure*

$$\overline{B(a,r)} = \{x \in X : \|x - a\| \leq r\}$$

is called a closed ball.

(ii) A point $a \in X$ *is called a limit point of A if, for every* $r > 0$,

$$B(a,r) \cap (A \setminus \{a\}) \neq \varnothing.$$

The set A is said to be closed if it contains all of its limit points.

(iii) The family

$$\mathrm{B} = \{B(a,r) : a \in X, r > 0\}$$

forms a subbasis for a Hausdorff topology τ *on X.*

Definition 2.3. *Let* $(X,\|\cdot\|)$ *be a normed linear space.*

(i) A sequence $\{x_n\}$ *in X is said to converge to* $x \in X$ *if for every* $r > 0$ *there exists* $n_0 \in \mathrm{N}$ *such that*

$$\|x_n - x\| < r \qquad \text{for all } n > n_0.$$

In this case, we write $\lim_{n\to\infty} x_n = x$ *or* $x_n \to x$.

(ii) A sequence $\{x_n\}$ *in X is called a Cauchy sequence if for every* $r > 0$ *there exists* $n_0 \in \mathrm{N}$ *such that*

$$\|xn - xn+m\| < r$$

for all $m,n \in \mathrm{N}$ *with* $n > n_0$.

(iii) If every Cauchy sequence in X converges in X, then $(X,\|\cdot\|)$ *is called a complete normed linear space, or simply a Banach space.*

Definition 2.4. *[10] Let* $(X,\|\cdot\|)$ *be a normed linear space. The Hausdorff metric on CB(X), the family of all nonempty closed and bounded subsets of X, is defined by*

$$H(A,B) = \max\left\{\sup_{x\in A} d(x,B),\ \sup_{y\in B} d(y,A)\right\}, \tag{1}$$

for all $A,B \in CB(X)$, *where*

$$d(x,B) = \inf\{\|x - \beta\| : \beta \in B\} \tag{2}$$

for every $x \in X$.

A fuzzy set in X is a function from X into the interval $[0,1]$. The collection of all fuzzy sets in X is denoted by $F(X)$. If A is a fuzzy set and $x \in X$, then $A(x)$ is called the grade of membership of x in A. The α-level set of a fuzzy set A, denoted by $[A]_\alpha$, is defined as

$$[A]_\alpha = \{x \in X : A(x) \geq \alpha\}, \qquad \alpha \in (0,1],$$

and

$$\overline{[A]_0} = \{x \in X : A(x) > 0\}.$$

Let X be a nonempty set and let Y be a normed linear space. A mapping T from X into $F(Y)$ is called a fuzzy mapping. Thus, for each $x \in X$, the set $T(x)$ is a fuzzy subset of Y and $T(x)(y)$ denotes the membership value of y in $T(x)$. For simplicity, the α-level set of $T(x)$ is written as $[Tx]_\alpha$ instead of $[T(x)]_\alpha$.

Definition 2.5. *[12] A point* $x \in X$ *is called a fuzzy fixed point of a fuzzy mapping* $T : X \to F(X)$ *if there exists* $\alpha \in (0,1]$ *such that* $x \in [Tx]_\alpha$.

Two fuzzy mappings S and T are said to have a common fuzzy fixed point if there exists $\alpha \in (0,1]$ *such that* $x \in [Sx]_\alpha \cap [Tx]_\alpha$.

Lemma 2.1. *[12] Let A and B be nonempty closed and bounded subsets of a metric space (X,D). If* $a \in A$, *then*

$$D(a,B) \leq H(A,B).$$

Lemma 2.2. *Let A and B be nonempty closed and bounded subsets of a normed linear space* $(X,\|\cdot\|)$. *If* $a \in A$, *then*

$$d(a,B) \leq H(A,B).$$

Proof. This result follows immediately from Lemma 2.1 and Definition 2.4. □

Lemma 2.3. *[12] Let A and B be nonempty closed and bounded subsets of a metric space (X,D) and let* $0 < \alpha \in \mathbb{R}$. *Then, for each* $a \in A$, *there exists* $b \in B$ *such that*

$$D(a,b) \leq H(A,B) + \alpha.$$

Lemma 2.4. *Let A and B be nonempty closed and bounded subsets of a normed linear space* $(X,\|\cdot\|)$ *and let* $0 < \alpha \in \mathbb{R}$. *Then, for each* $a \in A$, *there exists* $b \in B$ *such that*

$$\|a - b\| \leq H(A,B) + \alpha.$$

Proof. This result follows immediately from Lemma 2.3. □

III. MAIN RESULTS

Theorem 3.1. *Let* $(X,\|.\|)$ *be a complete normed linear space i.e. Banach space. Let* $S,T : X \to F(X)$ *be fuzzy mappings and for* $x \in X$, *there exist* $\alpha_S(x), \alpha_T(x) \in (0,1]$ *satisfying the following condition:*

$$H([Tx]_{\alpha_T(x)},[Sy]_{\alpha_S(y)}) \leq a_1 d(x,[Tx]_{\alpha_T(x)}) + a_2 d(y,[Sy]_{\alpha_S(y)}) + a_3 d(x,[Sy]_{\alpha_S(y)}) + a_4 d(y,[Tx]_{\alpha_T(x)}) + a_5\|x-y\| \quad (3)$$

for all $x,y \in X$. *Also,* $0 \leq a_i \in \mathbb{R}$, *where* $i = 1,2,\ldots,5$ *with* $a_2 + a_3 < 1$, $a_1 + a_4 < 1$ *and* $\tau = \frac{a_1+a_2+a_3+a_4+2a_5}{2-(a_1+a_2+a_3+a_4)} < 1$. *Then S and T have a common fixed point.*

Proof. Let x_0 be any arbitrary point in X, such that $x_1 \in [Tx_0]_{\alpha(x0)}$. Then by Lemma 2.4 there exists $x_2 \in [Sx_1]_{\alpha(x1)}$, such that

$$\|x_1 - x_2\| \leq H([Tx_0]_{\alpha(x0)},[Sx_1]_{\alpha(x1)}) + (a_1 + a_3 + a_5)$$
$$\leq a1d(x0,[Tx0]\alpha(x0)) + a2d(x1,[Sx1]\alpha(x1)) + a3d(x0,[Sx1]\alpha(x1)) + a_4 d(x_1,[Tx_0]_{\alpha(x0)})) + a_5\|x_0 - x_1\| + (a_1 + a_3 + a_5) \quad (4)$$
$$\leq a\,\|x-x\|\,a\,\|x-x\|\,a\,\|x-x\|\,\|x-x\|$$
$$+ a_5\|x_0 - x_1\| + (a_1 + a_3 + a_5$$

$$||x_1 - x_2|| \leq \frac{a_1 + a_3 + a_5}{1 - (a_2 + a_3)}||x_0 - x_1|| + \frac{a_1 + a_3 + a_5}{1 - (a_2 + a_3)}. \quad (5)$$

Similarly, by symmetry we have

$$||x_2 - x_1|| \leq H([Sx_1]_{\alpha(x_1)}, [Tx_0]_{\alpha(x_0)}) + (a_1 + a_4 + a_5)$$
$$\leq a_1 d(x_1, [Sx_1]_{\alpha(x_1)}) + a_2 d(x_0, [Tx_0]_{\alpha(x_0)}) + a_3 d(x_1, [Tx_0]_{\alpha(x_0)}) + a_4 d(x_0, [Sx_1]_{\alpha(x_1)}) + a_5||x_1 - x_0|| + (a_1 + a_4 + a_5$$
$$||x_2 - x_1|| \leq \frac{a_2 + a_4 + a_5}{1 - (a_1 + a_4)}||x_0 - x_1|| + \frac{a_2 + a_4 + a_5}{1 - (a_1 + a_4)}. \quad) \quad (6)$$

Adding (5) and (6), we get that

$$||x_1 - x_2|| \leq \frac{a_1 + a_2 + a_3 + a_4 + 2a_5}{2 - (a_1 + a_2 + a_3 + a_4)}||x_0 - x_1|| + \frac{a_1 + a_2 + a_3 + a_4 + 2a_5}{2 - (a_1 + a_2 + a_3 + a_4)}. \quad (7)$$

Now,

$$\tau = \frac{a_1 + a_2 + a_3 + a_4 + 2a_5}{2 - (a_1 + a_2 + a_3 + a_4)} < 1$$

Then by (7), we have

$$\|x_2 - x_3\| \leq \tau\|x_0 - x_1\| + \tau.$$

Again by Lemma 2.4, $x_3 \in [Tx_2]_{\alpha(x2)}$ such that

$$||x_2 - x_3|| \leq H([Sx_1]_{\alpha(x_1)}, [Tx_2]_{\alpha(x_2)}) + \frac{(a_1 + a_2 + a_3 + a_4 + 2a_5)^2}{2 - (a_1 + a_2 + a_3 + a_4)}$$
$$\leq \tau^2||x_0 - x_1|| + 2\tau^2.$$

Continuing in the preceding way, we can obtain a sequence $\{x_n\}$ such that $x_{2n+1} \in [Tx_{2n}]_{\alpha(x2n)}$ and $x2n+2 \in [Sx2n+1]\alpha_{(x2n+1)}$, with

$$\begin{aligned}||x_{2n+1} - x_{2n+2}|| &\le H([Tx_{2n}]_{\alpha(x_{2n})}, [Sx_{2n+1}]_{\alpha(x_{2n+1})}) \\ &\quad + \frac{(a_1+a_3+a_5)^{2n+1}}{(1-(a_2+a_3))^{2n}} \\ &\le a_1 d(x_{2n}, [Tx_{2n}]_{\alpha(x_{2n})}) + a_2 d(x_{2n+1}, [Sx_{2n+1}]_{\alpha(x_{2n+1})}) \\ &\quad + a_3 d(x_{2n}, [Sx_{2n+1}]_{\alpha(x_{2n+1})}) + a_4 d(x_{2n+1}, [Tx_{2n}]_{\alpha(x_{2n})}) \\ &\quad + a_5 ||x_{2n} - x_{2n+1}|| + \frac{(a_1+a_3+a_5)^{2n+1}}{\{1-(a_2+a_3)\}^{2n}}\end{aligned}$$

$$||x_{2n+1} - x_{2n+2}|| \le \frac{(a_1+a_3+a_5)}{\{1-(a_2+a_3)\}}||x_{2n} - x_{2n+1}|| + \frac{(a_1+a_3+a_5)^{2n+1}}{\{1-(a_2+a_3)\}^{2n+1}}. \quad (8)$$

Similarly,

$$\begin{aligned}||x_{2n+2} - x_{2n+1}|| &\le H([Sx_{2n+1}]_{\alpha(x_{2n+1})}, [Tx_{2n}]_{\alpha(x_{2n})}) \\ &\quad + \frac{(a_2+a_4+a_5)^{2n+1}}{\{1-(a_1+a_4)\}^{2n}} \\ &\le a_1 d(x_{2n+1}, [Sx_{2n+1}]_{\alpha(x_{2n+1})}) + a_2 d(x_{2n}, [Tx_{2n}]_{\alpha(x_{2n})}) \\ &\quad + a_3 d(x_{2n+1}, [Tx_{2n}]_{\alpha(x_{2n})}) + a_4 d(x_{2n}, [Sx_{2n+1}]_{\alpha(x_{2n+1})}) \\ &\quad + a_5 ||x_{2n+1} - x_{2n}|| + \frac{(a_2+a_4+a_5)^{2n+1}}{\{1-(a_1+a_4)\}^{2n}}\end{aligned}$$

$$||x_{2n+2} - x_{2n+1}|| \le \frac{(a_2+a_4+a_5)}{\{1-(a_1+ba_4)\}}||x_{2n} - x_{2n+1}|| + \frac{(a_2+a_4+a_5)^{2n+1}}{\{1-(a_1+a_4)\}^{2n}}. \quad (9)$$

By (8) and (9)

$||x2n+1 - x2n+2|| \le \tau||x2n - x2n+1|| + \tau 2n+1$. Therefore,

$$\begin{aligned}||x_n - x_{n+1}|| &\le \frac{(a_1+a_2+a_3+a_4+2a_5)}{\{2-(a_1+a_2+a_3+a_4)\}}||x_{n-1} - x_n|| \\ &\quad + \left(\frac{(a_1+a_2+a_3+a_4+2a_5)}{\{2-(a_1+a_2+a_3+a_4)\}}\right)^n. \\ ||x_n - x_{n+1}|| &\le \tau||x_{n-1} - x_n|| + \tau^n \\ &\le \tau[\tau||x_{n-2} - x_{n-1}|| + \tau^{n-1}] + \tau^n \\ &= \tau^2||x_{n-2} - x_{n-1}|| + 2\tau^n \\ &\cdots \\ &\cdots \\ ||x_n - x_{n+1}|| &\le \tau^n||x_0 - x_1|| + n\tau^n. \quad (10)\end{aligned}$$

Now, for any positive integers m,n $(n > m)$, we have

$$\begin{aligned}||x_m - x_n|| &\le ||x_m - x_{m+1}|| + ||x_{m+1} - x_n|| \\ &\le ||xm - xm+1|| + \{||xm+1 - xm+2|| + ||xm+2 - xn||\} \\ &\le ||x_m - x_{m+1}|| + \{||x_{m+1} - x_{m+2}|| + \ldots + ||x_{n-1} - x_n||\} \\ &\le \tau^m||x_0 - x_1|| + m\tau^m + \tau^{m+1}||x_0 - x_1|| + (m+1)\tau^{m+1} + \cdots + \tau^{n-1}||x_0 - x_1|| + (n-1)\tau^{n-1} \text{ by (10)} \\ &\le \tau^m(1 + \tau + \cdots + \tau^{n-m-1})||x_0 - x_1|| + \sum_{i=m}^{n-1} i\tau^i\end{aligned}$$

Since $\tau < 1$, it follows from the Cauchy root test that $\sum i\tau^i$ is convergent and hence x_n is a Cauchy sequence. Since $(X,\|.\|)$ is complete, there exists $z \in X$ such that $x_n \to z$ as $n \to \infty$.

Now,

$$\begin{aligned}d(z,[Sz]\alpha(z)) &\le ||z - x2n+1|| + d(x2n+1,[Sz]\alpha(z)) \\ &\le ||z - x2n-1|| + H([Tx2n]\alpha(x2n),[Sz]\alpha(z))]\end{aligned}$$

Using (3) with $n \to \infty$ we get

$$\{1-(a_2+a_3)\}d(z,[Sz]_{\alpha(z)}) \le 0$$

So, we get

$$z \in [Sz]\alpha(z).$$

This implies that $z \in X$ is a fixed point for S. Similarly, we can show that $z \in [Tz]_{\alpha(z)}$. Hence, $z \in X$ is a common fixed point for the fuzzy mappings S and T. □

Example 2. *Let $X = [0,1]$ and $\|x - y\| = |x - y|$, whenever $x,y \in X$, then $(X,\|.\|)$ is a complete normed linear space. We define a fuzzy mapping $T,S : X \to F(X)$ respectively by*

$$T(x)(t) \begin{cases} 1, & 0 \le t \le \frac{x}{4} \\ \frac{1}{2}, & \frac{x}{4} \le t \le \frac{x}{3} \\ \frac{1}{4}, & \frac{x}{3} \le t \le \frac{x}{2} \\ 0, & \frac{x}{2} \le t \le 1 \end{cases}$$

$$S(x)(t) = \begin{cases} 1, & 0 \le t \le \frac{x}{20} \\ \frac{1}{3}, & \frac{x}{20} < t \le \frac{x}{10} \\ \frac{1}{6}, & \frac{x}{10} < t \le \frac{x}{5} \\ 0, & \frac{x}{5} < t \le 1 \end{cases}$$

for all $x \in X$, there exists $\alpha(x) = 1$ such that $[Tx]_{\alpha(x)} = [0, \frac{x}{4}]$ and $[Sx]_{\alpha(x)} = [0, \frac{x}{20}]$. Then

$$\begin{aligned} H([Tx]_{\alpha(x)}, [Sy]_{\alpha(y)}) \le{}& \frac{1}{5}|x - \frac{x}{4}| + \frac{1}{10}|y - \frac{y}{20}| \\ &+ \frac{1}{15}|x - \frac{y}{20}| + \frac{1}{20}|y - \frac{x}{4}| \\ &+ \frac{1}{25}|x - y| \end{aligned}$$

Since, all the conditions of Theorem 3.1 are satisfied, T and S have a common fixed point. One can easily check that 0 is a common fixed point of T and S.

IV. CONCLUSIONS AND FUTURE DIRECTIONS: RELEVANCE TO AI TECHNOLOGY

The common fixed point theorem proved in this paper can be viewed as a useful theoretical tool in AI systems that involve uncertainty, vagueness, or imprecise information. In many intelligent algorithms, such as fuzzy control, fuzzy decision-making and soft computing models, the state of the system is updated iteratively until a stable configuration is reached. The existence of a common fixed point guarantees, under suitable contractive conditions, that such iterative fuzzy processes admit a consistent and stable equilibrium.

In particular, the result may be applied to the convergence analysis of fuzzy neural networks, adaptive learning rules and reasoning mechanisms in AI technology. Since fuzzy mappings naturally model uncertainty in data and inference, the theorem provides a mathematical foundation for showing that two interacting fuzzy processes can converge to a common stable output. Thus, the theorem supports the stability and reliability of AI-based systems operating under ambiguity.

The future course of our research will be directed toward a more detailed study of the conditions ensuring that two fuzzy mappings possess a unique common fuzzy fixed point. The results obtained in this paper suggest several natural directions for extending common fuzzy fixed point theorems to other mathematical settings and for weakening the underlying contractive assumptions. Such developments would further strengthen the theoretical framework of fuzzy fixed point theory and may also lead to useful applications in other areas of mathematics and the applied sciences. In this regard, the subject remains a rich and promising field for further investigation.

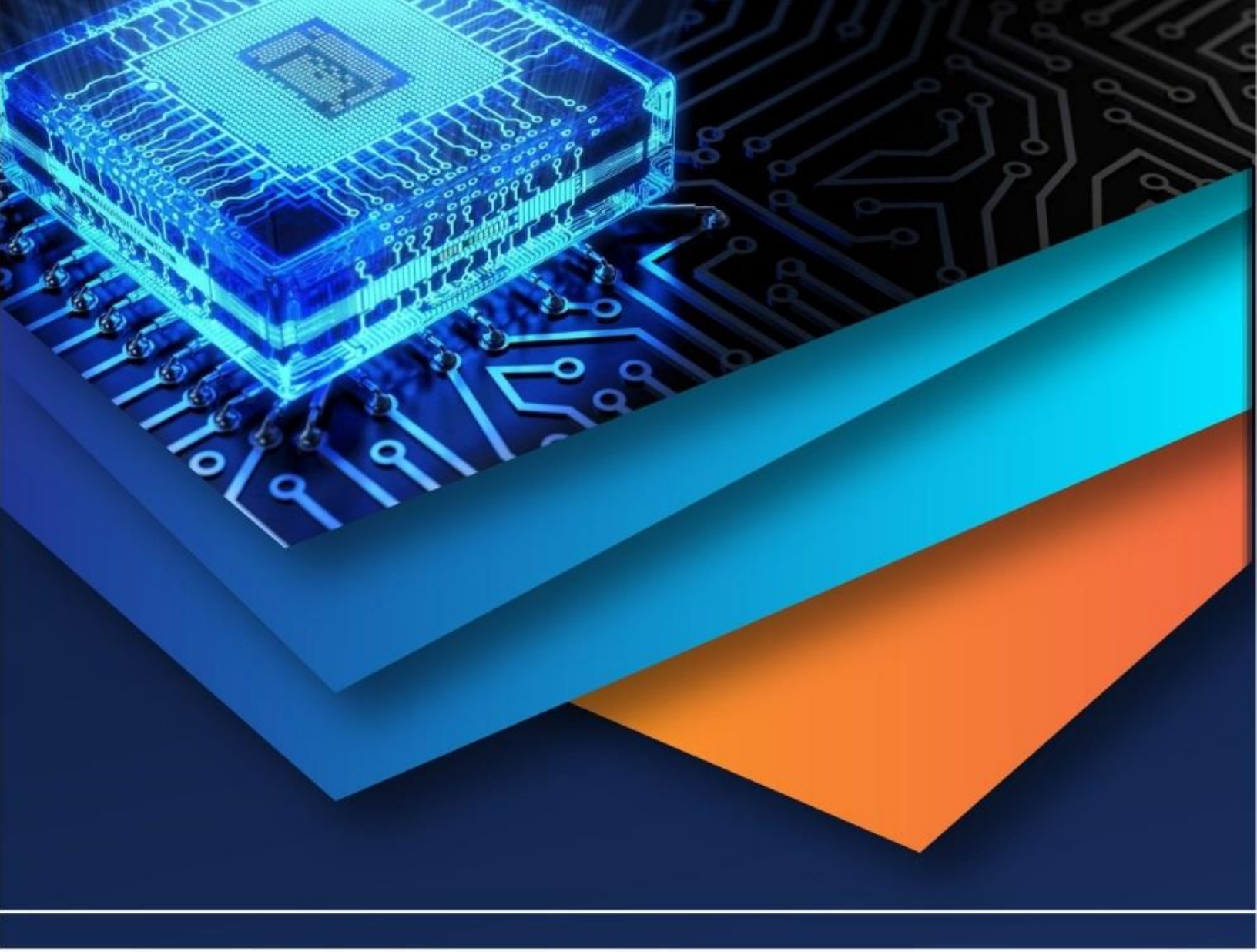
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