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Our Reasoning is Clearly Fuzzy, so Why Is Crisp Logic So Often Adequate?

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\begin{abstract}
Our reasoning is clearly fuzzy, so why is crisp logic so often adequate? We explain this phenomenon by showing that in the presence of noise, an arbitrary continuous (e.g., fuzzy) system can be well described by its discrete analog. However, as the description gets more accurate, the continuous description becomes necessary.
\end{abstract}

\section{Formulation of the Problem}

\textbf{Fuzzy logic is needed.} Our reasoning is clearly fuzzy. Whenever we use terms like “small”, “young”, etc., there is no crisp boundary: some people are clearly

1
young, some are clearly not young, but there is always an area in between in which a natural answer should be “young to a certain degree”.

Fuzzy logic has been specifically designed to capture this “fuzziness”; see, e.g., [2, 3, 7].

While fuzzy logic is successful, crisp methods are, surprisingly, successful as well. Fuzzy logic indeed has many useful applications. However, the puzzling fact is that in many other practical applications, crisp (non-fuzzy) methods work really well.

What we do in this paper. In this paper, we provide a possible explanation for this phenomenon.

Comment. Some of our results first appeared in [4].

2 Basis for Our Explanation: Tsirelson’s Theorem

Tsirelson’s observation. B. S. Tsirelson noticed [6] that in many cases, when we reconstruct the signal from the noisy data, and we assume that the resulting signal belongs to a certain class, the reconstructed signal is often an extreme point from this class. For example:

- when we assume that the reconstructed signal is monotonic, the reconstructed function is often (piece-wise) constant;
- if we additional assume that the signal is smooth (one time differentiable, from the class $C^1$), the result is usually one time differentiable but rarely twice differentiable, etc.

Geometric explanation for Tsirelson’s observation: general idea. Tsirelson provides an elegant geometric explanation to this fact: namely, when we reconstruct a signal from a mixture of a signal and a Gaussian noise, then the maximum likelihood estimation (a traditional statistical technique; see, e.g., [5]) means that we look for a signal that belongs to the priori class, and that is the closest (in the $L^2$-metric) to the observed “signal+noise”.

In particular, if the signal is determined by finitely many (say, $d$) parameters, we must look for a signal $\tilde{s} = (s_1, \ldots, s_d)$ from the a priori set $A \subseteq \mathbb{R}^d$ that is the closest (in the usual Euclidean sense) to the observed values

$$\tilde{o} = (o_1, \ldots, o_d) = (s_1 + n_1, \ldots, s_d + n_d),$$

where $n_i$ denotes the (unknown) values of the noise.
Since the noise is Gaussian, we can usually apply the Central Limit Theorem [5] and conclude that the average value of \((n_i)^2\) is close to \(\sigma^2\), where \(\sigma\) is the standard deviation of the noise. In other words, we can conclude that

\[
(n_1)^2 + \ldots + (n_d)^2 \approx d \cdot \sigma^2.
\]

In geometric terms, this means that the distance

\[
\sqrt{\sum_{i=1}^{d} (a_i - s_i)^2} = \sqrt{\sum_{i=1}^{d} n_i^2}
\]

between \(\vec{s}\) and \(\vec{o}\) is \(\approx \sigma \cdot \sqrt{d}\). Let us denote this distance \(\sigma \cdot \sqrt{d}\) by \(\varepsilon\).

**Geometric explanation: 2-D case.** Let us (for simplicity) consider the case when \(d = 2\), and when \(A\) is a convex polygon. Then, we can divide all points \(p\) from the exterior of \(A\) that are \(\varepsilon\)-close to \(A\) into several zones depending on what part of \(A\) is the closest to \(p\): one of the sides, or one of the edges.

Geometrically, the set of all points for which the closest point \(a \in A\) belongs to the side \(e\) is bounded by the straight lines orthogonal (perpendicular) to \(e\). The total length of this set is therefore equal to the length of this particular side; hence, the total length of all the points that are the closest to all the sides is equal to the perimeter of the polygon. This total length thus does not depend on \(\varepsilon\) at all.

On the other hand, the set of all the points at the distance \(\varepsilon\) from \(A\) grows with the increase in \(\varepsilon\); its length grows approximately as the length of a circle, i.e., as \(\text{const} \cdot \varepsilon\).

When \(\varepsilon\) increases, the (constant) perimeter is a vanishing part of the total length. Hence, for large \(\varepsilon\):

- the fraction of the points that are the closest to one of the sides tends to 0, while
- the fraction of the points \(p\) for which the closest is one of the edges tends to 1.

**Geometric explanation: general case.** Similar arguments can be repeated for any dimension. For the same noise level \(\sigma\), when \(d\) increases, the distance \(\varepsilon = \sigma \cdot \sqrt{d}\) also increases, and therefore, for large \(d\), for “almost all” observed points \(\vec{a}\), the reconstructed signal is one of the extreme points of the a priori set \(A\).

Much less probable is that the reconstructed signal belongs to the 1-dimensional face of the set \(A\), even much less probable that \(s\) belongs to a 2-D face, etc.

**Methodological consequences.** The main methodological consequence of this result is that even when the actual state space is continuous, when we determine
the state from measurements result, we inevitably obtain (most often) one of the
discretely many states. On the large-scale level, we get one of the few clusters.
When we add new measurements and thus, get to the next level, each original
cluster sub-divides into new clusters, etc., so that we get a hierarchical structure.

3 Our Explanation of the Success of Crisp Techniques

Tsirelson’s result explains why in spite of the clearly fuzzy character of most
human reasoning, binary logic describes most of this reasoning pretty well.
Indeed, states with unusual “truth values” (different from 0 and 1) are not
an exception, but rather a general rule. However, if we do the observations in
the presence of some noise (e.g., if we use a not-prefect procedure for describing
the values of the membership function), then we will mainly notice the extreme
points of the set \([0,1]\) of the truth values, i.e., the values 0 and 1.

4 In the Future, Fuzzy Techniques Will Be More and More Important

An interesting corollary is that as observations become more accurate, we will
observe the actual intermediate fuzzy values as well, and crisp description will
become more and more difficult.

Comment. Similarly, we can explain Schrödinger’s paradox in quantum me-
chanics (see Appendix).

5 Conclusion

In this paper, we provide a geometric explanation of why in many cases, in spite
of a fuzzy nature of human reasoning, crisp models work amazingly well.

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A Explanation of Schrödinger’s Paradox

In classical physics, it is assumed that for each state of a physical system, every property is either true or false. For example, a particle is either located in a certain interval of space coordinates \([x - \Delta, x + \Delta]\), or it is not located inside this interval.

In quantum mechanics, in addition to the states in which a particle is located within this interval, and to the states in which the particle is definitely outside it, there are states in which some measurements of the coordinate will lead to results within the interval, and some to the results outside this interval.

In such states, we cannot say that a statement “the particle is located in the given interval” is true or that this statement is false; at best, we can determine the probability of the “yes” answer. (To describe such unusual “truth value”, quantum logic has been introduced.)

States with unusual “truth values” are not an exception, but rather a general rule in quantum mechanics: e.g., for every two states \(\psi\) and \(\psi'\) with certain values \(\lambda \neq \lambda'\) of a measured quantity, there exists a state called their superposition in which the value of this quantity is no longer certain. (In the standard formalism of quantum mechanics, where states are described by vectors in a Hilbert space, superposition is simply linear combination.)

Such superposition state is easy to generate.
Schroedinger has shown that this superposition principle seemingly contradicts our intuition; see, e.g., [1].

Indeed, suppose that we have a cat in a box, and a light-controlled rifle is aimed at the cat in such a way that a left-polarized photon would trigger the rifle and kill the cat, while the right-polarized photon would keep the cat alive.

If we send a photon with a circular polarization (that is, according to quantum mechanics, a superposition of left- and right-polarized states), we would get (due to the linear character of the equations of quantum mechanics), the superposition of the states resulting from using left- and right-polarized photons. In other words, we will get a superposition of a dead and alive cat states. This is, however, something that no one has ever observed: for macroscopic objects (cats included), an object is either dead or alive. Tsirelson’s result explains why such non-extremal states are indeed difficult to observe.